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A review of the current automotive manufacturing practice from an energy perspective

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HIGHLIGHTS

- Vehicle manufacturing process is described focusing on the energy sources and use.
- The paint shop is reviewed focusing on components, paints and energy utilisation.
- Energy efficiency and thermal management practice are highlighted.
- Future steps towards the realisation of a low-carbon automotive sector are discussed.

ARTICLE INFO

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Sustainable automotive industry
Energy efficiency
Heat recovery
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ABSTRACT

The automotive industry is facing on-going challenges to improve the sustainability of its manufacturing processes and vehicle emissions due to economic, environmental, marketability and policy concerns. This review aims to evaluate steps that could be taken by automotive manufacturers to further reduce energy consumed during manufacturing processes, particularly focusing on thermal management of low-temperature heat sources that are extensively present in the whole plant and in the paint shop. Through an extensive literature review on the subject, this article presents vehicle production processes, the past and future drivers, and strategies towards sustainability. Firstly, the whole vehicle manufacturing process is explained focusing on the energy sources and their use in the plant. Then, the paint shop is described as being responsible for the highest energy consumption in the production process, focusing on components, paints and energy utilisation. After presenting the practice performed by automotive manufacturers to reduce the energy consumption of their production process in terms of energy efficiency and thermal management, the article is closed by future steps that could be undertaken by the automotive industry towards the realisation of a low-carbon sector. It is concluded that unexploited potential for heat recovery in the paint shop is present in the low-temperature range and this waste heat could be effectively exploited by liquid desiccant technology for energy consumption reduction and could increase paint quality of the painting process due to more efficient moisture control.

1. Introduction

Automotive manufacturing is a complex and energy-intense process which consumes a significant quantity of raw materials and water. To remain competitive, automotive original equipment manufacturers (OEMs) have to strive for better product quality by continuously improving their production process and driving towards low-carbon emissions and enhanced sustainability [1]. The timeline taken up by the automotive industry towards sustainability is shown in Fig. 1. The revolution was started with vehicle mass production in the 1940s (requiring faster curing time of painting process and better film performance in terms of corrosion and durability of the paint) [2], followed by electrodeposition coating (E-coat) in the 1960s (showing environmental benefits due to lower quantities of volatile organic compounds (VOCs) and hazardous air pollutants) [2], reduced vehicle emissions in the 1970s [3], improved energy efficiency in the 1980s [4], waste minimisation and better resource management (reuse, recycling, and remanufacturing) in the 1990s, and environmental legislation in the 2000s [5], which has gradually moved the industry towards sustainability.

Fig. 2 displays the number of vehicles produced in the UK, for instance, and the corresponding energy consumption together with the

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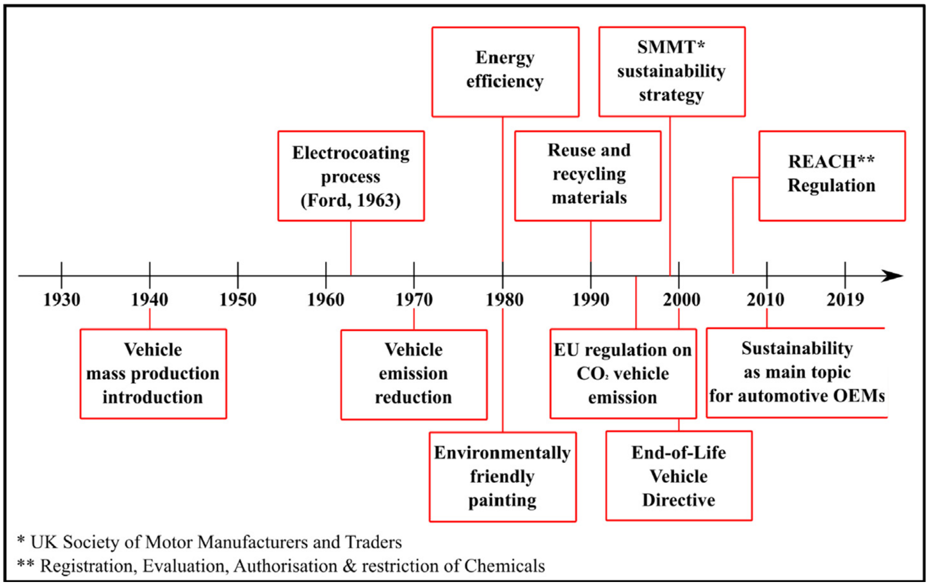
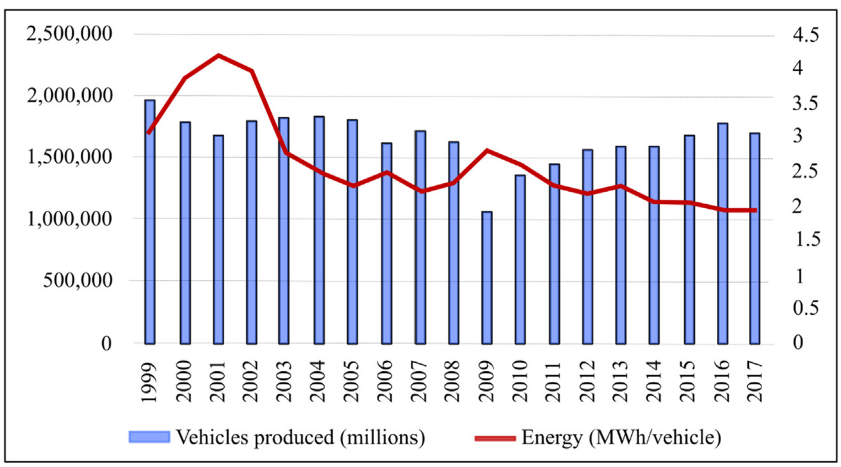


Fig. 1. The automotive revolution since 1940.



Year	2000	2016	2017
Total vehicles produced (millions)	1.8	1.81	1.75
Total energy used (GWh)	7,013	4,515	4,354
Energy use per vehicle (MWh/unit)	3.9	1.97	1.95
Total water use (m^3)	6,090	5,553	5,112
Water use per vehicle (m^3/unit)	5.3	2.4	2.3
Total $CO_{2,eq}$ produced (tonnes)	2,182,926	1,282,050	1,123,425
$CO_{2,eq}$ per vehicle (tonnes/unit)	1.1	0.55	0.5
Volatile organic compounds (VOCs) emissions (g/m^2)	55.0	32.9	34.6
Total combined waste-to-landfill (tonnes)	80,399	4,092	4,147
Waste-to-landfill per vehicle (kg/unit)	40.3	1.4	1.3
Average new car CO_2 emissions (g/km)	181	120.1	121.0

Fig. 2. Vehicles production, energy consumption and environmental burden of the manufacturing process in the UK during the period of 1999–2017, adapted from [6].

environmental burden of the manufacturing process in 1999–2017 based on statistics provided by the UK Society of Motor Manufacturers and Traders (SMMT), which established a sustainability strategy in 1999, bringing together the already established sustainability strategies of automotive OEMs [6]. It is shown that more vehicles have been produced since the economic recession of 2008–2009, which approached 1.8 million vehicles in 2017, whilst energy consumption and emissions per vehicle have been declining together with VOCs emissions, water consumption and waste production. Perpetually, the automotive industry in the UK as well as around the world is facing new challenges due to an increase in the overall vehicle production, energy cost and environmental responsibilities.

To date, a number of reviews have been reported primarily focussing on sustainability of automotive industry. For instance, Orsato [7] provided a brief description of the sustainable automotive industry, highlighting steps undertaken by the industry in terms of vehicle design, manufacture, use and disposal. Main topics related to sustainability in the automotive industry were reviewed by [5], which identified manufacturing, materials use, recyclability strategies and sustainability models employed by automotive OEMs. Jasiński et al. [8] reviewed sustainability assessment criteria used in the automotive industry, assisted by interviews of experts of the sector to develop a sustainable framework. Akafuah et al. [9] reviewed the automotive painting process, describing the different steps required for optimal quality and current and future trends towards sustainability. Other reviews are more focused on specific aspects of the automotive industry or manufacturing process, such as modularity [10], use of sustainable [11] and multifunctional materials [12], recycling [13], assembly [14], welding [15], energy consumption, management and recovery of vehicles in the driving phase [16], environmental impact of the painting process [17] and its transfer efficiency [18]. Giampieri et al. [19] reviewed energy efficiency and environmental policies which were applicable to the UK automotive sector. As such, a complete energy-related review of the vehicle manufacturing process is missing.

Built on existing reviews towards sustainability, this article aims to address the current knowledge gaps by covering energy efficiency, heat recovery, and future development of the sector. The paper is structured as follows. Section 2 presents the scope and methodology of the review. Section 3 describes the conventional vehicle manufacturing and painting processes, focusing on energy sources, processes and current and future strategies towards sustainability in terms of energy efficiency, heat recovery, and higher utilisation of renewable energies. Section 4 supplements the review with a summary on the evolution of the sector towards sustainability in terms of driving (lightweight, autonomous and electric vehicles) and manufacturing (modification of the manufacturing process, circular economy and Industry 4.0).

2. Scope and methodology

A framework, as shown in Fig. 3, was designed and applied to outline the methodology implemented for this review. It aimed to identify possible energy recovery opportunities currently unexploited or not effectively exploited in automotive manufacturing plants which could further increase economics and sustainability of the manufacturing process. The identification of energy recovery opportunities as presented in this review is the first step towards potential exploitation of innovative technology for the industry. Whilst technology innovation and scientific nature of the literature are topics that deserve independent reviews, they are not the focus of this article and therefore will not be included here.

The investigation of the main relevant works on sustainability of the automotive industry was conducted by searching for keywords such as sustainability, energy efficiency, heat recovery, environmental impact, energy consumption modelling, painting, low-carbon related to the automotive industry etc. on indexed web search engines, such as Google Scholar and Scopus, which resulted in 164 references published during the period of 1988–2018. The literature is categorised as in Fig. 4 and Table 1, which is further described in Appendix A.

It was found that the evolution of the automotive industry (which extended to 14 main identified topics as shown in Fig. 4) has affected industrial, national and international institutions. Whilst national and international research has eased the development of the sustainability in the automotive industry with the realisation of policies, regulations, standards, etc., automotive OEMs developed new strategies for sustainable development of their industry based on tools for sustainability and energy consumption assessment. Different energy efficient practices in manufacturing, painting and heat recovery identified for sustainable production practices have been undertaken by automotive OEMs after characterising vehicle manufacturing and painting processes, energy and material consumption, and environmental impact.

Whilst processes, facilities and their related energy consumption are described, the primary focus has been given to the paint shop, which is the largest energy consumer. By evaluating what steps were done during the last decades and what is going to be done in the future by automotive OEMs towards energy efficiency and sustainability, the possible steps required to further reduce the environmental impact of

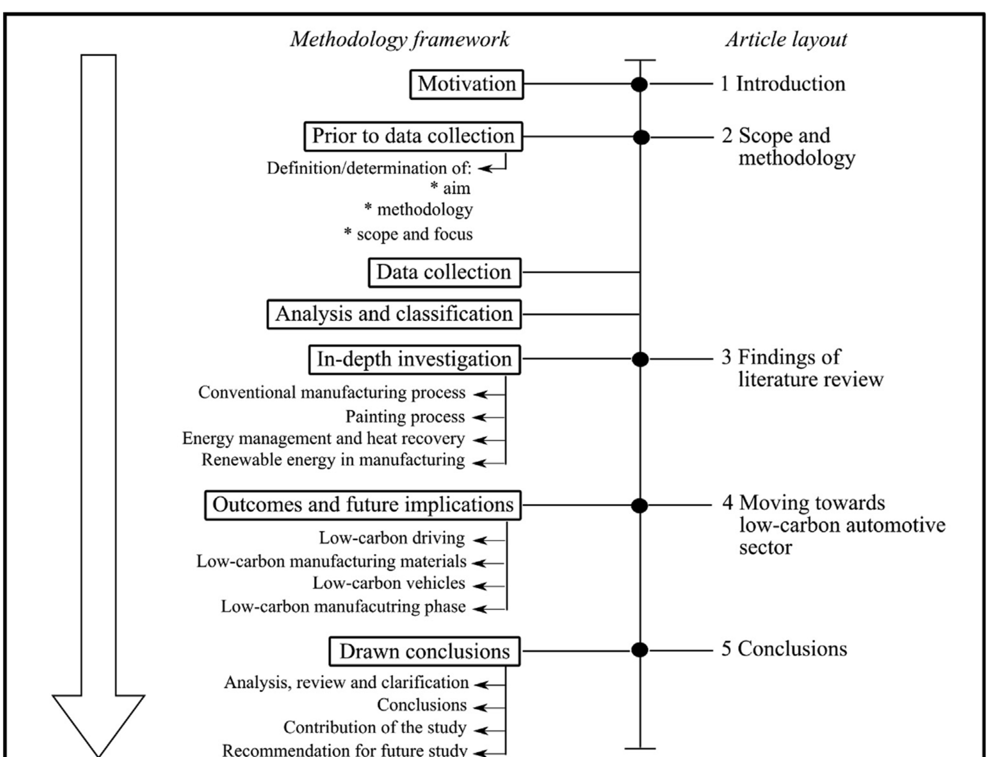


Fig. 3. Methodology framework applied for the study matching up with the layout of this article.

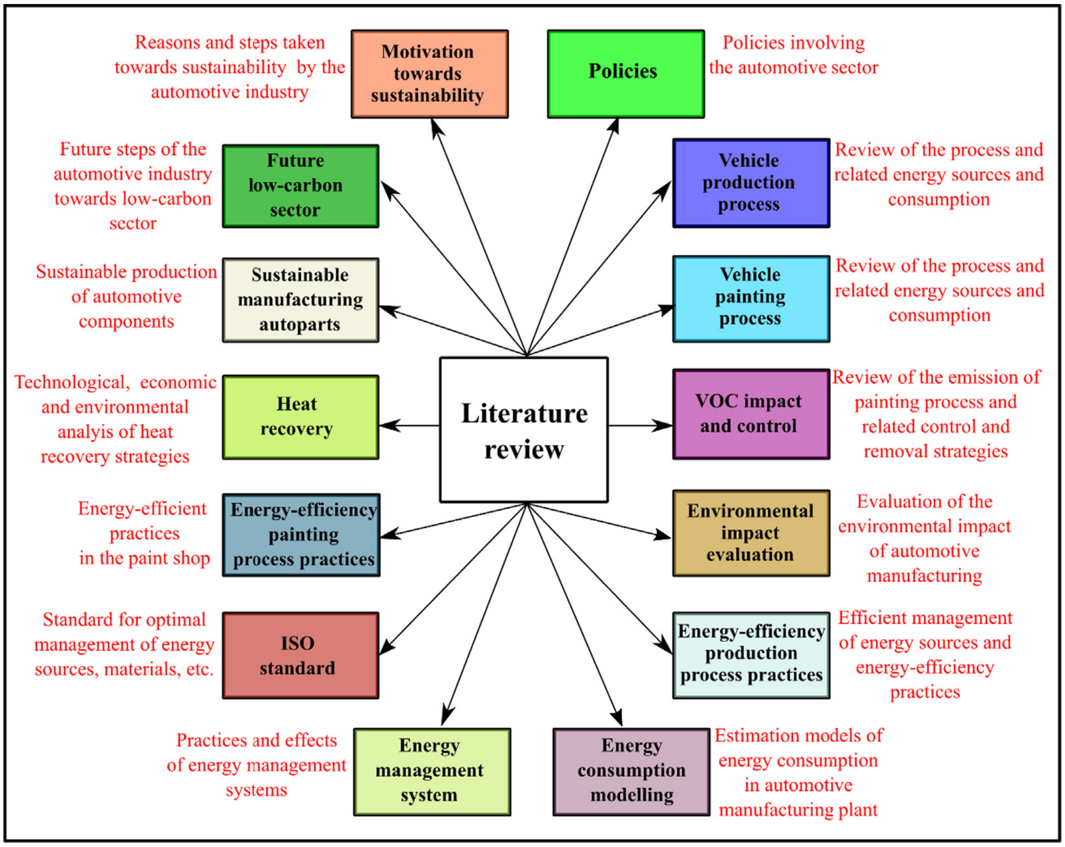


Fig. 4. Classification by topic of the literature review on the sustainability of the automotive sector.

the manufacturing process were identified. The paper principally highlights the classification of low-temperature waste heat sources present in the manufacturing plant and the identification of an effective strategy to utilise them. In addition, it is important to note that all the considerations made are also valid for similar sectors, such as heavy trucks, ships, aircraft, etc., extending the significance of the study.

3. Findings of literature analysis

3.1. The automotive manufacturing plant: Facilities and energy use

The automotive manufacturing process involves a long and complex supply chain. It includes the production of raw materials (e.g. steel, aluminium, plastic, and glass), fabricated parts, components, and subsystems (internal/external processes); the assembly of these parts, components, and subsystems; and finally the distribution and sale of the vehicles [20]. The sector affects and is affected actively by other energy-intensive industrial sectors, such as steel, glass, and petroleum-related industries which supply plastic and rubber (for tires production). The economic and environmental concerns for the automotive sector will therefore largely influence these sectors [7]. A representation of the complex automotive production supply chain is shown in Fig. 5 [20].

Energy employed in an automotive plant can be classified as primary and secondary, as shown in Table 2 for various applications. Primary energy source use includes electricity and fuel, i.e. 56% and 44% respectively for the automotive OEMs industry in the United States in 2011, for instance [21]. Meanwhile, compressed air, chilled and hot water, and steam are examples of secondary energy carriers, which are produced from the primary sources to carry energy throughout the plant. It is worth noting that automotive OEMs tend to adopt different manufacturing processes and materials in practice due to diversity in vehicle models, volumes, availability of external suppliers, energy sources, use of renewable energy, and climate. Nevertheless, the parameters characterising the manufacturing processes and their energy consumption reported in this article present a general scenario rather than manufacturer-specific cases to enhance existing knowledge on general automotive manufacturing processes.

Due to the extensive consumption of secondary energy carriers, most vehicle manufacturing plants power their production lines by employing an on-site energy conversion and transmission system [22,23]. Power and steam are usually generated at a central location and then transported to individual facilities (i.e. building systems, equipment and services) for a specific purpose. Meanwhile, systems driven by compressed air and motor (conveyors, material handling, robots, etc.) are usually located closer to consumption [20].

Electricity consumption for facilities and systems common to the whole plant infrastructure is distributed among painting (27–50%), heating, ventilation and air-conditioning (11–20%), lighting (14–15%), compressed air (9–14%), welding (9–11%), and materials handling/tools (7–8%) [4]. Although this analysis is closely linked to a specific vehicle production which is usually different among automotive OEMs, some common features can be identified. For instance, heating, ventilation and air-conditioning (HVAC) and lighting are common building services in all vehicle production plants, required for operation to provide an optimal working environment in terms of safety and comfort [20]. The use of common facilities in the plant is here described:

- The energy consumption for lighting is dependent on the facility requirements, building structure and availability of daylights [24]. Facilities with intensive manual labour (e.g. the assembly shop) consume more electricity for lighting [25].
- The HVAC unit supplies air to paint booths and provides air-conditioning to work areas. The optimal performance of the HVAC unit is required to ensure worker productivity and painting quality of the final product.

Table 1
Literature focus of the study.

Tier*	Level**	Primary recipient***	Literature focus
I	I	M	• Taxations [117–118], agreements [44,119] and trade schemes [45] involving energy efficiency and carbon emission of the automotive industry • Vehicles emissions [95,120], end life use of vehicle's materials [121] and chemicals use [40] • ISO Standards related to the automotive sector: energy [53], environmental [54] and quality management systems [55] and application [122] • Review of policies and Standards for the automotive sector [19]
II	II	T	• Sustainable automotive industry: development reasons [3,7], research within the sector [1,5,8], future trends [123] and evolution of new markets [124] • Tool development for sustainability assessment analysis [125] and green logistic practices [126] based on CO_2 emissions, energy and water consumption [100] and alternative production strategies [127] • Energy management system (EMS) development for energy consumption reduction [128], good practices [129–130], and role, structure and future development [56] • Evolution of manufacturing processes [103], medium- [96,105] and long-term strategies [104,109,131], national and industry alliances [93], better-performing engines [102], lightweight vehicles [94,98–99], electrification [101,132], future modifications [35,97,106], higher digitalisation [112–113], and strategies for waste and material consumption reduction [108,110–111]
III	III	T	• Vehicle production: process energy consumption and energy carriers [16,20,27], potential applications [4], manufacturing plant [30,33], specific processes [14–15,29], key variables involved in the automotive manufacturing [26], modelling approach [133], waste production [134], life cycle analysis (LCA) of the process [135–136] and evaluation of medium- and long-term optimisation strategies [22,24]. Case study of body [31,137] and final assembly shops [25] • Paint shop: components [2,36], ventilation [32], dipping [68], spraying, drying and curing [43,138], effect of painting processes on energy [39,139], electricity consumption [140], energy reduction strategies [23], paint quality [34,37,141], paint drying [142], transfer efficiency [18], paint waste reduction [143] and future modification [144–145] • Paint reformulation [42,146], painting evolution [9,41], life cycle assessment of the paint [147–148] and of the painting process [17,149] • Volatile organic compounds (VOCs) produced by the painting process [49] and control strategies [115,150] • Sustainable materials [151] and production of components e.g. metal joining [62–63], gears [152] and engine valves [153]
IV	III	R	• Energy efficiency evaluation: performance indicators [50–51], simulation [154–155], combination of stochastic and deterministic frontier [21,52], parameters affecting the energy consumption of the process [156–157], research towards sustainability [158], framework development [159] and case studies [160–162] • Energy-efficient practices: production management [163], holistic approach [164–165], water usage and energy integrated analysis [166–167], use of virtual engineering [168–169] and discrete event simulation [170–171], use of algorithms [172], reformulation [173], modularity [10], multifunction materials [11–12], predictive energy management schemes [174], flywheels [58], compressed air systems [28,175–176], welding [61], water usage [64] and material reuse [13] • Energy-efficient painting [72]: air recirculation from the paint booth [46–47], innovative paint reformulation [41,65], alternative oven [177–179], oven design [66–67,180], over-sprayed paint collection [69–70,181] and VOC removal system [48,71] • Heat recovery and renewable energy: heat exchanger network [82,182], high- [73–74,107], medium- [79–81], and low-temperature exhaust [38,87,116], heat pumps [83–84], paint shop heat cascade strategy [91–92] and use of renewable energy [57], such as solar [183] and hydroelectric energy [184] • Future vehicles: innovative materials [185] and design [186] for lightweight vehicles, connected and autonomous vehicles [187] and digitisation of the automotive industry [188]

* Tiers I—IV include I Policies and standards; II Mission and management strategies; III Production practice; and IV Research and development (R&D).
** Levels I—III cover I National; II Organisational; and III Team.
*** Primary recipient refers to those being affected significantly, who are categorised as Manufacturers (M); Technical Staff (T); and Research staff (R).

- Motors are one of the largest energy electricity consumer in the manufacturing plant, particularly in the assembly shop. Motors find application in different systems, such as HVAC, compressed air, fans, pumps, robots, etc. and processes, such as stamping, of the manufacturing plant [4,23].
- Electricity consumed for materials handling and tools is related to conveyors and robots. Conveyors (i.e. belt, chain or hanging) transports materials, parts, and equipment by converting electrical

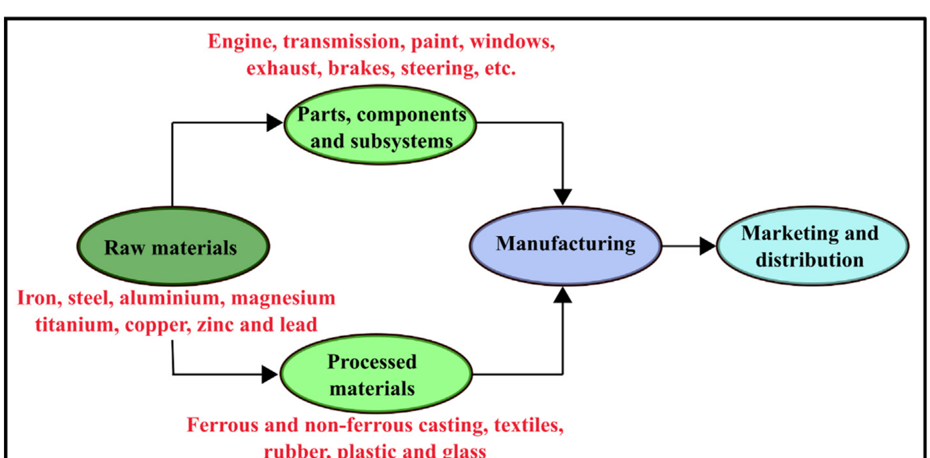


Fig. 5. Processes involved in the automotive production supply chain, adapted from [20].

Table 2
Application-related energy use of fuel and electricity in the automotive manufacturing plant.

Source	Primary/secondary application
Electricity (56%)	● Compressed air o Conveyors o Over-sprayed collection system o VOC removal o Paint spraying ● Chilled water o Air conditioning o Paint mix room ● Materials handling ● Painting (fans, IR curing, etc.) ● Welding ● Metal forming ● Ventilation ● Lighting
Fuel (44%)	● Steam o Painting o Space heating o Car washing o Non manufacturing activities ● Hot water o Pretreatment (painting) o Space heating ● Metal casting ● Direct space heating ● VOC removal ● Ovens

energy into mechanical energy. Depending on the application, overhead or floor conveyors are commonly used [2]. The energy consumption is dependent on power and usage time [26]. Robots are used to move heavy parts or spray the sealant or the paint during sealing and painting processes [24,26]. Factors, such as the length and speed of the moving material, motor efficiency, handling time, etc. determine how much energy would be consumed for the work [26].

- Fans are responsible for high energy consumption in the manufacturing plant, particularly for the painting process, given the high flow rates of ventilation air required by it. Pumps are also used extensively in the paint shop to deliver chilled water or hot water to air supply units, to feed chemicals to the over-sprayed paint collection system or to supply paint from the paint mix room to the paint booth [23].
- Compressed air systems are also common to the whole manufacturing plant. Compressed air is extensively used in the plant in different operations (stamping, assembling and painting) and for different applications, such as motors, cleaning, spraying, etc. [27,28]. Compressed air is clean and safe but very inefficient as only about 10% of the power input is converted into useful energy [4].
- Welding techniques are used widely in the automotive industry to obtain permanent joint of vehicle body components. The common joining techniques are spot welding, laser beam welding, metal inert gas (MIG) or metal active gas (MAG) welding, riveting and screwing [24]. The welding process is responsible for energy and compressed air consumption [22]. As analysed by [26], the energy consumption for welding shows a linear dependency on the number of parts produced over a period of time. The always growing request for lighter and stronger materials is requiring modifications to the welding process used by automotive OEMs. The subject will be further discussed in Section 4.

Fig. 6 shows a conventional automotive manufacturing plant with a breakdown of the total energy consumption, adapted from [20,21]. For completeness, the analysis should additionally take account of energy consumed for raw materials processing and external processes. However, this is not an easy task due to (i) the drastic influence of the outdoor climatic conditions on vehicle production and the energy being consumed by different facilities and processes; and (ii) the different typologies of processes (onsite or offsite) adopted for manufacturing vehicle components [27].

As shown in Fig. 6, the production of vehicle parts during internal and external processes differentiates the vehicle manufacturing process. Automotive OEMs produce most of the parts whilst some components (e.g. brake system, steering, suspension, etc.) are manufactured by affiliated companies. Vehicle manufacturing processes are described as follows:

- An on-site stamping shop may be established, depending on the manufacturers and their production process [20]. In the shop, different sheet-metal manufacturing processes are performed to produce 250–300 parts per car body [29]. The material, starting from steel coils, is gradually transformed into a body part, such as hood, fender, roof, etc. [30]. If performed on-site, the stamping process is responsible for high consumption of compressed air.
- The body shop is the facility where the raw materials provided by an external supplier are transformed to form the vehicle body, which is referred to as body-in-white (BIW). The process involves the assembly of many components by different welding operations. The plant usually consists of 15–20 sub-assembly lines; each with characteristic operation [31]. Currently, the materials mostly used are steel and aluminium [24], whilst plastic is used for doors, bumpers, etc. [4]. However, automotive OEMs are moving toward utilising plastic and other lighter and cheaper materials, such as aluminium and fibreglass (see Section 4). The manufacturing process in the body shop may include metal treating, casting, forming, joining, etc. [4]. Depending on the manufacturing process, assembly can be done both manually and automatically with robots. Conveyors are used to move the assembled bodies along the welding stations. The electricity required for welding, robots, conveyors, etc. is the main energy consumption in the facility. The BIW structure is then transferred to the paint shop.
- Powertrain covers all components, such as engine, transmission, differential, etc., involved in converting engine power into motion. In the powertrain shop, engine and transmission parts cast and manufactured by automotive OEMs (mostly subsidiaries) or external suppliers are assembled to form the powertrain [20]. Metal casting, treatment, forming and forging are energy-intensive processes applied in producing powertrain components: (i) casting is performed during engines and other components manufacturing processes where electricity and fuel are used for different operations, such as sheet forming, welding, material handling, transport, etc. [27], (ii) machining/cutting/tooling operations which involve metal cutting, grinding, drilling, etc. are performed under a “dry” or “wet” condition, depending on the use of a cutting fluid (the metalworking fluid used as process coolant) [32]. Natural gas and steam are consumed if parts and components (engine, transmission, etc.) are manufactured on-site. In the chassis shop, the powertrain and other parts, such as wheels, brakes, exhaust, steering system, suspension, etc., are mounted on a steel frame through a pressing process. This frame, called chassis, forms the basis of the vehicle, providing stability to the drive. Electricity is consumed during these assembly processes.
- The paint shop offers a pleasant appearance and protection against weather and corrosion to BIW and other components. It is the facility which involves painting and sealing operations and consumes the largest quantity of energy during vehicle manufacturing processes. More discussion is presented in Section 3.2. The painted vehicle body is transported from the paint shop to the final assembly shop by using conveyors.
- The final assembly shop is the last production step where the painted vehicle body is mounted with all the assembled sub-

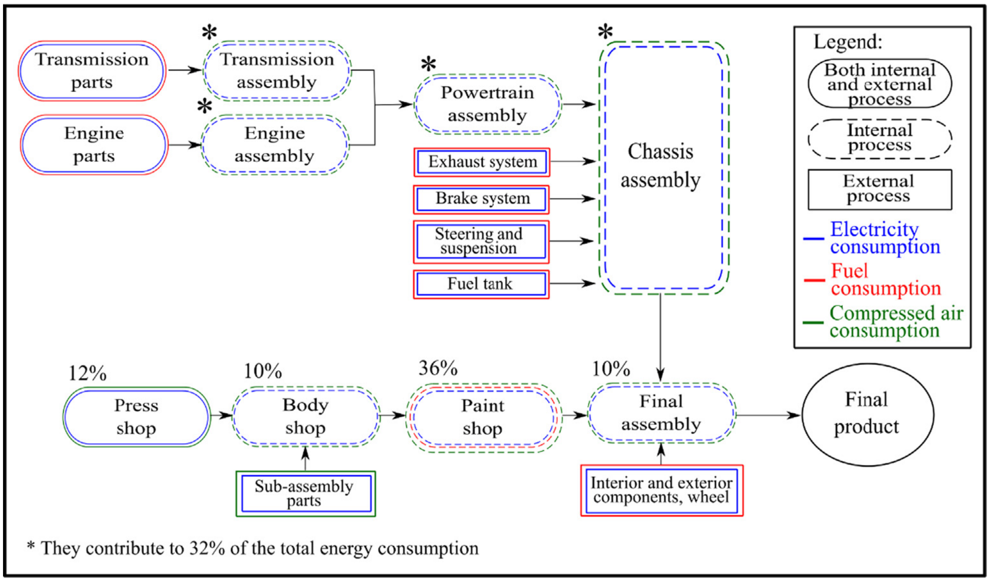


Fig. 6. Schematics of a conventional automotive manufacturing plant.

components (i.e. powertrain and external components) conveyed by the chassis shop. The assembly processes range from highly automated to manual. The latter is the main activity performed in the final assembly shop [20]. Fluids, such as coolant and brake fluid, are added to the vehicle in the process [33]. At the end of the assembly shop, vehicle inspection and testing are performed, which are usually the final step of the production process before the delivery and sale of the vehicle. If parts and components (e.g. dashboard assemblies, seats, tires, windshields, etc.) are manufactured on-site, natural gas and steam are consumed [20]. However, electricity and compressed air are mainly used due to the use of robots and conveyors. Most materials handling and joining processes are common to both the body and the final assembly shops. As more manual assembly is required with less robotic equipment, the final assembly shop consumes less electricity while requiring a higher consumption for lighting in the facility [20,25].

3.2. The paint shop and its energy use

Paint provides aesthetic (optical quality and attractiveness) and physical properties (corrosion resistance, mechanical protection, and protection against weather conditions) to the vehicles. Paint deposition and curing processes involve various operation steps, components (paint booths, ovens, scrubbers, VOC removal system, etc.) and significant consumption of electricity, fuel, compressed air, hot and chilled water. Given the complexity of the process, the paint shop management is often performed by dedicated companies, such as Dürr, Eisenmann, Taikisha, etc. [2]. Fig. 7 shows the results of a Dürr's analysis of the energy sources consumption and related costs in a paint shop [23].

Painting and working booths and ovens show high electricity and natural gas consumption. On the other hand, the highest amount of hot water is consumed during the pre-treatment process, as described afterwards. An analysis of the electricity and natural gas consumption by facilities of a local automotive manufacturer is shown in Fig. 8.

The main energy sources used in the paint shop and the related applications are described below:

- Electricity is used to power the fan motors and produce secondary energy sources in the painting process [23]. As previously shown in Fig. 7, the high air volume flow rate required by paint booths, working decks and ovens is responsible for the highest electricity consumption in the paint shop. Lighting, pumps, conveyors, VOC removal system, and chiller present a share percentage lower than 5%. Additional electricity is used for computer-controlled systems [20].
- Natural gas is used to heat up the air before being delivered to (i) the paint spray booth, particularly in winter (see air supply units in Section 3.2.1) and (ii) ovens. Natural gas is also used for hot water production which is crucial for pre-treatment during the painting process (see Section 3.2.1). Also, 2% of the natural gas is used to remove VOC produced during the painting process with a thermal oxidation process.
- Compressed air is also highly utilised to atomise the paint particles in an atomiser and spray them onto the vehicle body. Additional operations performed with compressed air in the paint shop are cleaning, repairing, spraying, over-sprayed paint removal, VOC removal, etc.

3.2.1. Painting process and thermal energy management

An exemplified case of the conventional painting process is illustrated in Fig. 9. The main painting lines in the paint shop are pre-treatment, E-coat, primer, top coat and final inspection line. The final product consists of five paint coating layers, each with different thickness and functions, as shown in Fig. 10 [23].

After the body shop, the BIW needs to remove contaminants from its metal surface and ease the adhesion of the next paint layer on it [2]. This process is called pre-treatment and involves different stages (usually 8–12), such as a pre-cleaning stage, 2–3 degreasing stages, an activation stage, a phosphating stage, a passivation stage (optional), several rinsing stages, and a final draining stage [2]. The pre-cleaning and degreasing processes remove oil, grease, lubricants, etc. from the vehicle to prepare for the deposition of the next coatings. After cleaning, a phosphate layer coat (usually zinc phosphate, $Zn_3(PO_4)_2$) is applied to the vehicle BIW by means of a dipping process [24]. The zinc phosphating process passivates the vehicle metal surface and produces a thin non-metallic crystalline phosphate layer (2–3 μm) that chemically adheres to the steel of the BIW, increasing its corrosion resistance [34]. The phosphating is preceded by the activation process, which assists the formation and growth of phosphate crystals on the BIW [2,35]. It is fundamental to keep pH and temperature of the phosphating bath, the concentration of chemical agents and the time of the dipping process under control to ensure the quality of the pre-treatment [35]. The process involves water pumping and heating which are supplied by electricity and natural gas combustion, respectively [24]. The

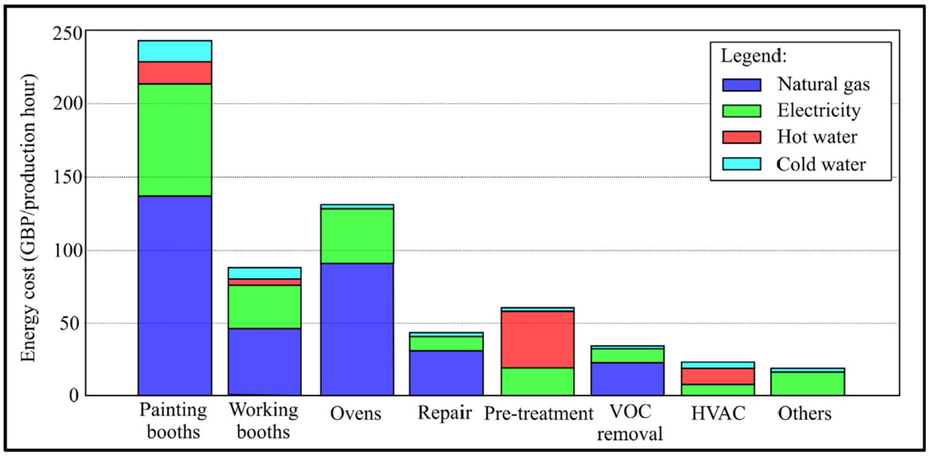


Fig. 7. Energy-related cost for paint shop facilities, adapted from [23].

largest quantity of hot water is consumed during pre-treatment (as previously shown in Fig. 7). This is because it is a priority to keep the temperature of the phosphating bath to approximately 45 °C for the chemical reactions [24,36]. Table 3 summarises the working fluid and temperature ranges required by the different processes during pre-treatment.

The pre-treatment process is ended by washing with deionised (DI) water and air blow drying process to remove the remained phosphating chemicals, such as Cl or Na salts, before sending the BIW to the E-coat line [35]. During E-coat, the vehicle body is dip coated by means of the cataphoretic paint deposition process to produce a nearly uniform layer (20–25 μm), which main aim is to provide corrosion resistance [2]. Two different E-coat processes have been developed depending on the process charge: (i) anodic electrodeposition, which was first invented in 1963, and (ii) cathodic electrodeposition, which developed later but has supplanted the previously used process due to its greater resistance to corrosion [2]. The driving force of the process is the electric current passing through the body of the vehicle (made as the positive or negative electrode) and the electrodeposition paint solution, which allows the paint to deposit on the surface [36].

The process is influenced by the direct voltage applied, the E-coat paint composition, the pH and conductivity of the paint, and the dipping time and temperature of the E-coat bath, which must be maintained between 26.7 and 37.8 °C [2,35]. To do that, the E-coat paint circulation system is equipped with a temperature control unit and a cooling system, which removes the heat increase due to the pumps, the deposition process and electrical resistance of the tank and the film [2]. Ultrafiltration equipment is used to recover paint ingredients, producing an ultra-filtrated material called permeate, which is flushed back to the E-coat tank to increase the material efficiency of the process [2,35]. An example of the E-coat process is shown in Fig. 11.

The main function of the E-coat is to provide corrosion and chip resistance improvement [2]. Chip resistance is a key factor to avoid corrosion. In fact, when a vehicle with low resistance to chips or gravel is hit and exposed to natural agents, such as water, salt, and oxygen, the vehicle body will start to corrode [2]. The advantages of E-coat are excellent adhesion to metal [37], high resistance to displacement by water [37], and better behaviour in terms of pollution (reduced VOCs and HAPs emission) and health and safety (reduced fire hazard) [2]. As for the pre-treatment line, the E-coat deposition process is ended up by DI water rinse and air blow-off to remove water and avoid water spotting [35]. Spot sanding operations after E-coat are usually minor [36].

After the deposition process, ovens are used to cure the paint before sending the vehicle to sanding operation. The temperature profile of the E-coat curing varies with painting processes performed by different automotive manufacturers. A common condition is the *metal temperature* of 165–175 °C, i.e. the temperature of the metal vehicle body, for a

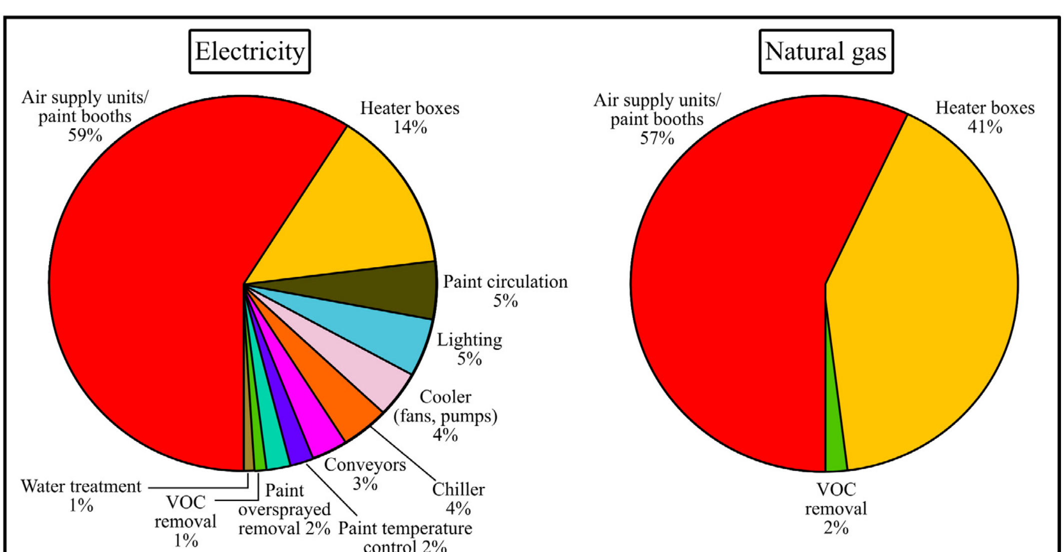


Fig. 8. Electricity (left) and natural gas consumption (right) analysis of a paint shop.

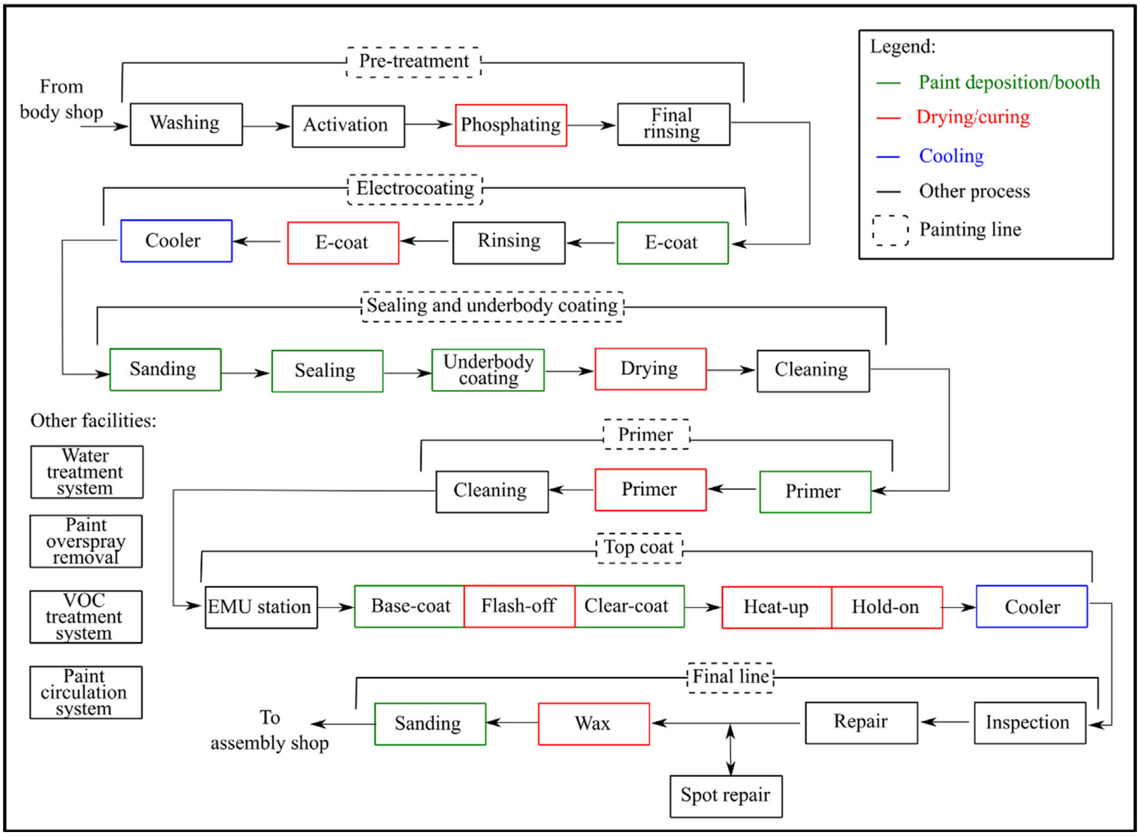


Fig. 9. Conventional vehicle painting process.

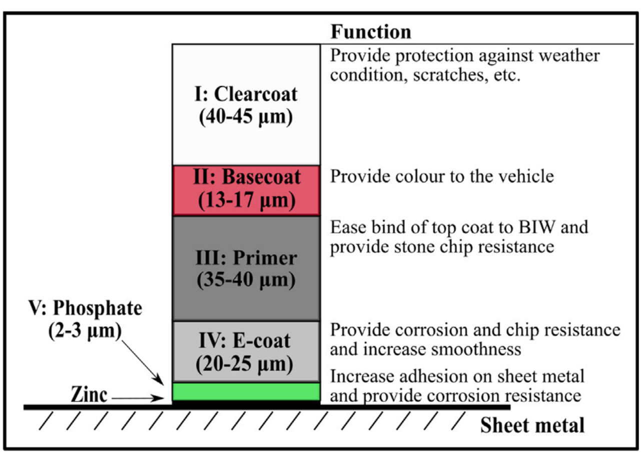


Fig. 10. Paint coating layers, thicknesses and functions.

Table 3
Temperature profile of pre-treatment process steps, adapted from [9].

Process	Fluid	Temperature (°C)
Pre-degreasing	Hot water	43–49
Degreasing	Degreaser water	40.5–46.1
Treatment	Phosphate zinc solution	40.5–46.1

period of 10 min [2]. Chip resistance and layer adhesion of the E-coat are particularly sensitive to this temperature window [2]. Fuel and electricity are consumed in the E-coat oven to heat and blow the air, respectively [24]. If pre-treatment and E-coat lines are integrated in a heat recovery project, remarkable economic savings in the painting process can be achieved [38]. The heat released by the pre-treatment line can be utilised to produce the cooling effect required by the E-coat line (temperature control of the bath). The heat recovery and integration in a paint shop will be further discussed in Section 3.3.2.

After the E-coat line, sealants and underbody coat are applied to the underbody, welds and edges of vehicles (areas prone to corrosion) to increase resistance against water leaks and rust formation while providing better optical appearance [35]. Apart from sealing, the sealants present also additional functions, such as resistance to noise, vibration and hardness (NVH) and chipping [35]. Polyvinyl chloride (PVC) and acryl/urethane have been commonly employed as sealants [9]. The application of the sealant is performed in booths on both internal and external parts, with or without robots, to prevent air and water contact and rust formation [9].

After sealing and underbody coating, primer, base and clear coats are sprayed one by one for different purposes [39]. The primer coat (also referred to as surfacer) is characterised by the presence of anticorrosive pigments and provides a bond between the E-coat and the next paint layers, increasing the surface smoothness after E-coat painting and easing the deposition of the following paint layers. In addition, it improves the stone chip resistance, increasing the durability of the painting process [9]. After the primer coat deposition, a curing process is performed at an optimal condition as shown in Fig. 12 [2]. The previously applied sealants are usually cured together with the primer coat [2].

The base coat is painted over the primer coat to give the colour to the vehicle and it is followed by the clear coat deposition. Base coat and clear coat are often indicated together as top coat due to the single monocoque top coat exploited in the 1970s as the conventional painting process [2]. The clear coat is a transparent paint applied over the coloured base coat to protect the vehicle against external conditions, scratches, extensive sunlight, chemicals (e.g. acid rains and gasoline spillage), sudden changes in weather condition, etc. [2,37]. Due to economic reasons, clear coat deposition is performed with a *wet-on-wet*

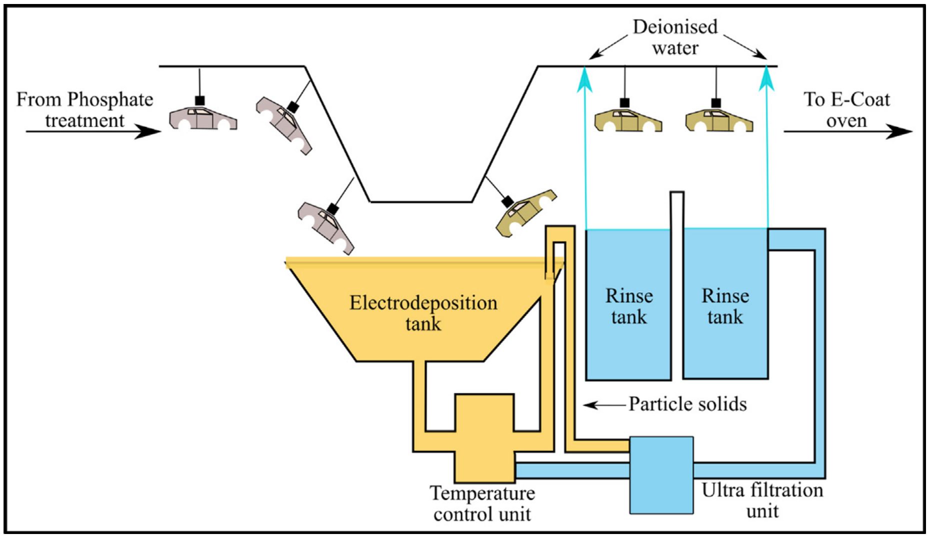


Fig. 11. Example of E-coat process, adapted from [9].

process [37]. It is required the evaporation of part of the base coat solvent before clear coat deposition in an intermediate process called flash-off, which leads to the cross-linking between the base and clear coat [2]. Depending on the paint used, the flash-off process (leading to a more than 90% solid content in the paint film) is performed in a drying booth with different temperature and time profiles, as shown in Table 4 [2].

Table 4 shows the effect of paint solvents on the flash-off process. Due to environmental reasons, medium solid (MS) solvent-based paint (which contains 15–20% of solid content), and high solid (HS) solvent-based paint require a shorter partial drying at lower temperature than water-based paint [9]. The different types of paint and their modifications to the painting process will be further treated in Section 3.2.2.

After clear-coat deposition, vehicles will be fully dried at 23 °C, cured in ovens and then cooled down to 23 °C, which ends the painting processes [2]. During the curing process, the wet paint film on the vehicle metal surface is heated up to the required temperature value, i.e. 130–180 °C in a heat-up zone and then maintained at this temperature for the required time in a hold-up zone. The cooling process is required to quickly allow vehicle handling and prevent heat release in the paint shop [36]. For low-production paint shops, the cooling effect can be provided by a temperature-controlled air seal [36]. A summary of the temperature and time profiles for the base- and clear-coat painting processes with water-based paint is shown in Table 5 [2].

Once cooled, the vehicle is inspected to check the need for possible

Table 4
Flash-off temperature and time requirements for different automotive paints, adapted from [2].

Paint	Time (min)	Temperature (°C)
Solvent-based medium solid (MS)	2–3	23
Solvent-based high solid (HS)	3–5	23
Water-based	3–8	50–80

Table 5
Common values for drying and curing process with water-based base- and clear-coats, adapted from [2].

Paint layer	Process	Time (min)	Temperature (°C)
Base-coat	Ambient flash-off	2	23
	Flash-off	5	75
	Air seal	1	23
	Cooling	2	23
	Air seal	0.5	23
Clear-coat	Ambient flash-off	8	23
	Oven	30	150
	Cooling	6	23

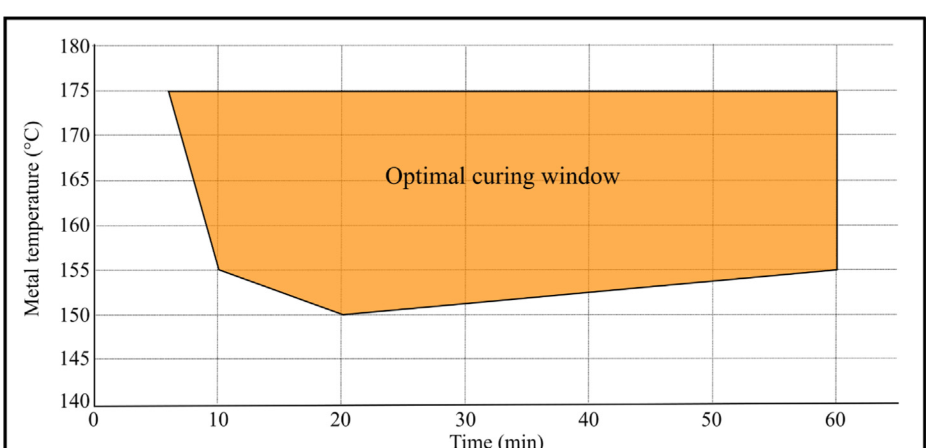


Fig. 12. Optimal operating conditions of primer coat curing, adapted from [2].

repair or rework. The process is ended by wax protection and sanding. Hot wax (at about 120 °C) is pumped into the vehicle's body section and cavities at risk of corrosion [36]. Once finished the painting process, the vehicle is mounted together with the chassis (powertrain and external components) in the final assembly shop and ready for distribution and sale.

3.2.2. Effect of the paint on the painting process

Traditional automotive paint consists of four chemical ingredients: carrier, resin, additives, and pigments [17]. The carrier, either solvent or water, differentiates between solvent- and water-based paint and determines their transferability and viscosity, while the resin keeps the colour pigment and determines the durability and optical quality of the paint [20]. Ingredients proportion varies with applications for the required characteristics.

Evolution of automotive painting has happened in the last century, modifying painting processes, paint composition, etc. In the past, solvent-based paint has been the conventional choice, mostly due to the higher evaporation rate of its solvent, resulting in a lower temperature and a shorter period required for drying and curing processes [37]. However, the spraying, drying and curing of solvent-based paint is responsible for VOCs emissions. The use of solvent-based paint has been limited by environmental regulations, resulting in the development of MS and HS solvent-based paint responsible for a lower environmental impact.

To comply with emission control requirements, particularly the EU Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Regulation [40], automotive OEMs have become more interested in alternative water-based paint, which has a lower solvent content, i.e. 20% as shown in Fig. 13. Therefore, water-based paint has a remarkable ability to reduce VOCs emissions.

In the last decades, powder-based paint containing no solvent has been developed as a sustainable replacement for liquid paint [17]. Powder-based paint presents economic, environmental and quality advantages, such as no VOC emission; higher resistance to corrosion, scratch and chip; improved paint transfer efficiency; and reduced waste. This is due to the ability to collect and re-utilise the over-sprayed powder paint in the painting process [41]. The process works differently compared to liquid paint since the powder is first liquefied after deposition and before being converted into a dry film [37]. Due to their characteristics, powder-based paint is increasingly used as the primer paint [35]. At the current technological state, the powder-based paint has technical limitations in the thickness of the produced film [41] and the difficulty to control it [17]. Painting with powder-based paint could result in defects, like orange peel, and produce a thicker layer, thereby off-setting the advantages resulting from the recollection and reuse of the over-sprayed material with a higher cost of the material for the thicker film [41]. In addition, this thicker film results in a higher temperature required by the curing process in the oven, resulting in higher energy consumption.

Thanks to the development of the more environmentally-friendly paint, it has been possible to reduce the VOCs emission from 500 g/m^2 for painted vehicle in the 1970s to the current value i.e. lower than 35 g/m^2, as required for new paint shops by EU regulations [2]. Fig. 14 shows the timeline of VOC emissions from the vehicle painting process in gram per square meter of vehicle body surface.

Due to higher environmental and painting quality performance in terms of colour and brilliance caused by their better rheology control, water-based paint has become the base- and clear-coat paint mostly used by automotive OEMs [2]. In the future, the powder-based paint could supplant water-based paint as the main worldwide used paint. However, research must be done on relevant subjects to overcome the current limitations of the technology.

As previously described, the painting steps and temperature and time profiles are significantly affected by the choice of paint resulting in different process and emissions. Paint evaporation and film formation depend on different factors, such as temperature near the surface, vapour pressure surface/volume ratio, surrounding air flow and humidity, which determine the quality of the final product [37]. Fig. 15 represents the paint evaporation and film formation processes and the related weight loss with water-based paint.

Fig. 15 shows the two-phrase process of paint evaporation and film formation: the first is based on an evaporation process, which rate is close to that of the solvent alone, according to Raoult's law. Once most of the solvent evaporates, the evaporation rate slows down, resulting in a diffusion-type process where the solvent loss is affected by the diffusion of paint molecules through the film [37]. For water-based paint, the flash-off process between base- and clear-coat depositions is determinant of the avoidance of paint defects. The water content in the base-coat must be partially dried before the deposition of the next layer in an evaporative-type process, making the temperature and humidity of the air surrounding the paint layer more important for the evaporation of the water in the wet film [37,42]. Also for powder-based paint, humidity plays a key role. As a matter of fact, humidity influences the resistivity of the paint particles, and consequently affects the adhesion of the coating, the paint transfer efficiency and the reproducibility of the film [43]. Accurate temperature and humidity control is required to obtain a reproducible defect-less paint layer. If the base-coat

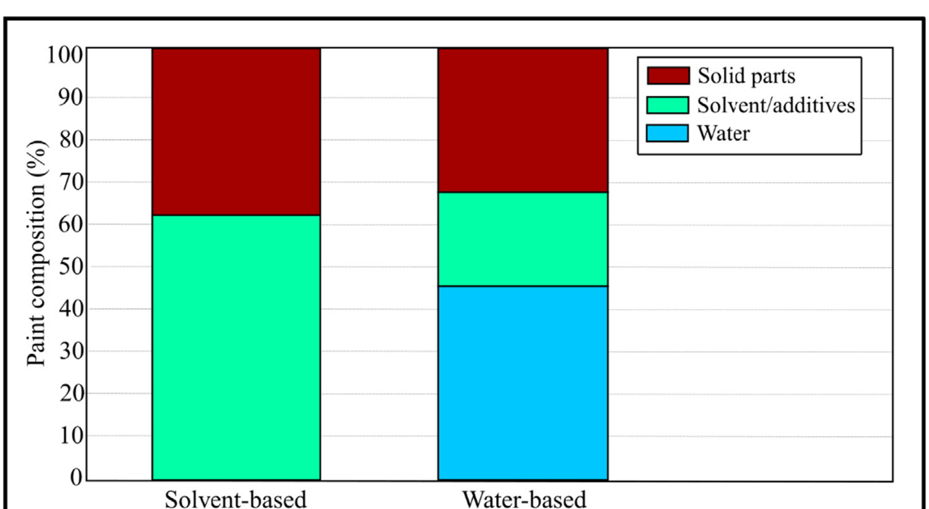


Fig. 13. Composition of solvent- and water-based paints, adapted from [43].

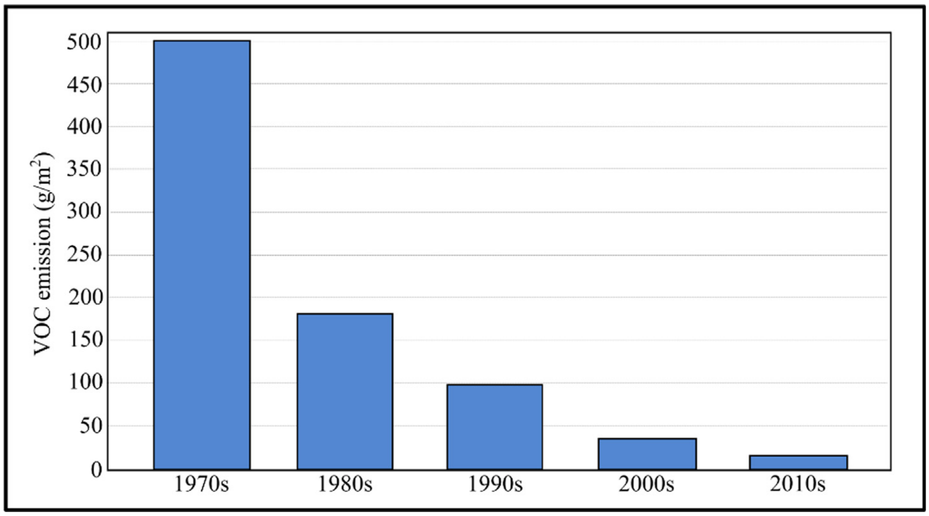


Fig. 14. Timeline of the VOCs emitted by the vehicle painting process, adapted from [2].

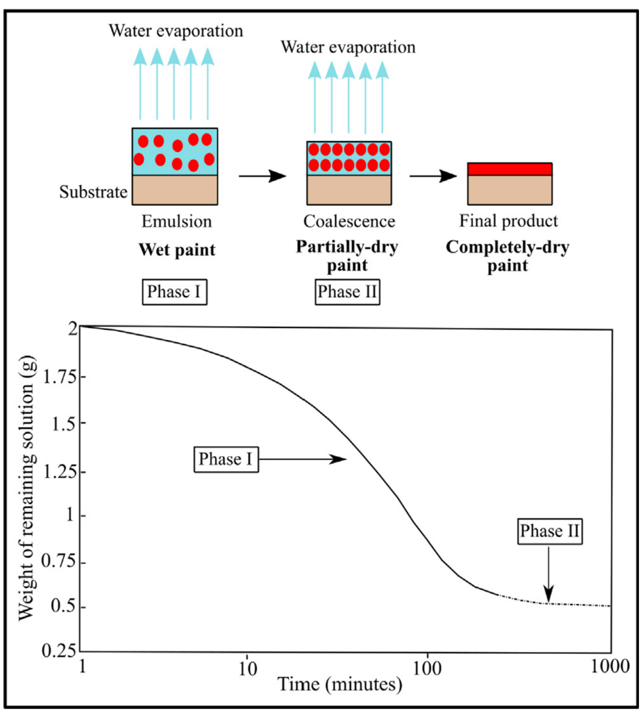
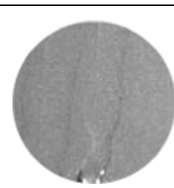


Fig. 15. Paint evaporation and film formation process, adapted from [37,43].

Table 6
Defects resulting on the vehicle body by inappropriate humidity control, adapted from [43].

Checking	Blistering	Collapse of the inner layers
		
Relative humidity too low	Relative humidity too high	Relative humidity too high

drying temperature is too high, the paint layer becomes porous, which affects the deposition of the clear-coat [37]. An inappropriate value of the humidity of the paint booth supply air produces paint defects, such as checking, blistering, popping, etc. Examples of paint defects due to improper humidity control are shown in Table 6. If too much water remains trapped in the paint film, it will spot the painted surface resulting in popping, blistering, collapse of the inner layers, etc. On the other hand, an overly dry environment could harden the paint layer too rapidly, resulting in cracks and lesions.

Vehicle reworking is necessary to remove paint defects, which is a time- and cost-consuming process. The importance of temperature and humidity control in paint booths and ovens for paint quality justifies the high amount of energy currently consumed by automotive OEMs.

3.2.3. Paint shop components

Performance optimisation of paint shop components, such as paint booths, air supply units, ovens, scrubbers, VOC removal systems, etc. is fundamental for energy consumption reduction. Paint booths are isolated enclosures for paint spraying operation to minimise exposure to VOCs and particulate matter (PM) present in the paint [9]. Depending on the configuration of the air supply unit which delivers air to the paint booth, technological solutions employing only external air or recovering exhaust air from the paint booth can be found in the automotive paint shop, as exemplified in Fig. 16.

Paint booths help to increase the transfer efficiency (TE) of paint with reduced over-sprayed paint and waste [44]. TE, which is defined as the percentage of paint that deposits on the vehicle body surface, is a characteristic of primary importance for the efficiency and costs of the painting process. TE depends on painting equipment (spray atomizers, robots, etc.), temperature, humidity and flow of the air in the paint booth, paint to be used and material to be painted [45]. Working decks for sanding, sealing, etc. present a structure analogous to booths and are mostly used for applications performed by humans [14]. Final inspection and rework are also realised in booths [14].

Supplying air by air supply units (ASUs) within consistent temperature and humidity ranges is a top priority for the painting process quality. The outdoor air is aspirated by fans, filtered in pocket filters, air-conditioned, and supplied into the spray painting booth [3]. Depending on the outdoor air conditions, ASUs must be able to fulfil different requirements during the year, such as filtration, heating/cooling, and (de)humidification. An example of a 100% outdoor ASU and the related process on a psychometric chart are shown in Fig. 17. The psychometric chart was obtained by considering an outdoor air condition of 5 °C and 80% relative humidity (RH), the paint booth

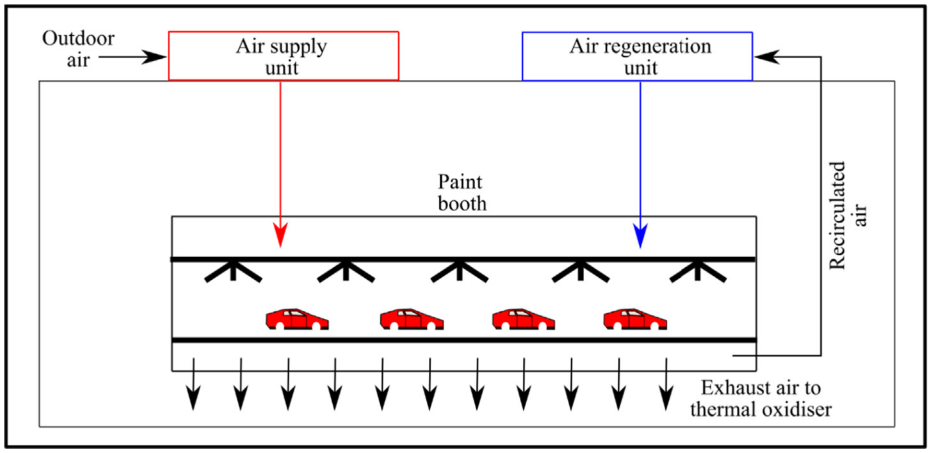


Fig. 16. A typical example of the paint booth and the relevant air management system.

optimal conditions (strong green) are defined as 23 ± 1 °C and 70 ± 2% RH, while the acceptable conditions (light green) are 23 ± 3 °C and 70 ± 5% RH. As previously described, it is fundamental to ensure these values in the paint booth to avoid paint defects.

Under the outdoor air conditions represented in Fig. 18, the air supplied to the paint booth is heated and humidified until the required values of temperature and humidity for the optimal painting process are achieved. The air is heated to 23 °C and then humidified isothermally by boiling water in a steam humidifier. Alternatively, the air is heated until the isenthalpic line is reached (about 40.9 °C) and then humidified/cooled by spraying water droplets in an adiabatic humidifier. The process is energy-intensive due to the high volume of air required in the paint shop (high electricity consumption for fans) and the continuous need for heating, cooling and humidification.

Air regeneration units (ARUs) have been developed to reduce energy consumption for air-conditioning, by recovering exhaust air from the paint booth. ARUs are less sensitive to outdoor air conditions [43]. The quantity of recovered air is a function of the system used to collect over-sprayed paint [46–47], which can typically recirculate 75–85% of the air back to the paint booth [23]. Fig. 18 shows an ARU for the paint booth and the related psychometric chart considering recirculated air at 27 °C and 60% RH.

The exhaust air from the paint booth must be cooled down and dehumidified to remove sensible heat gains in the building before being

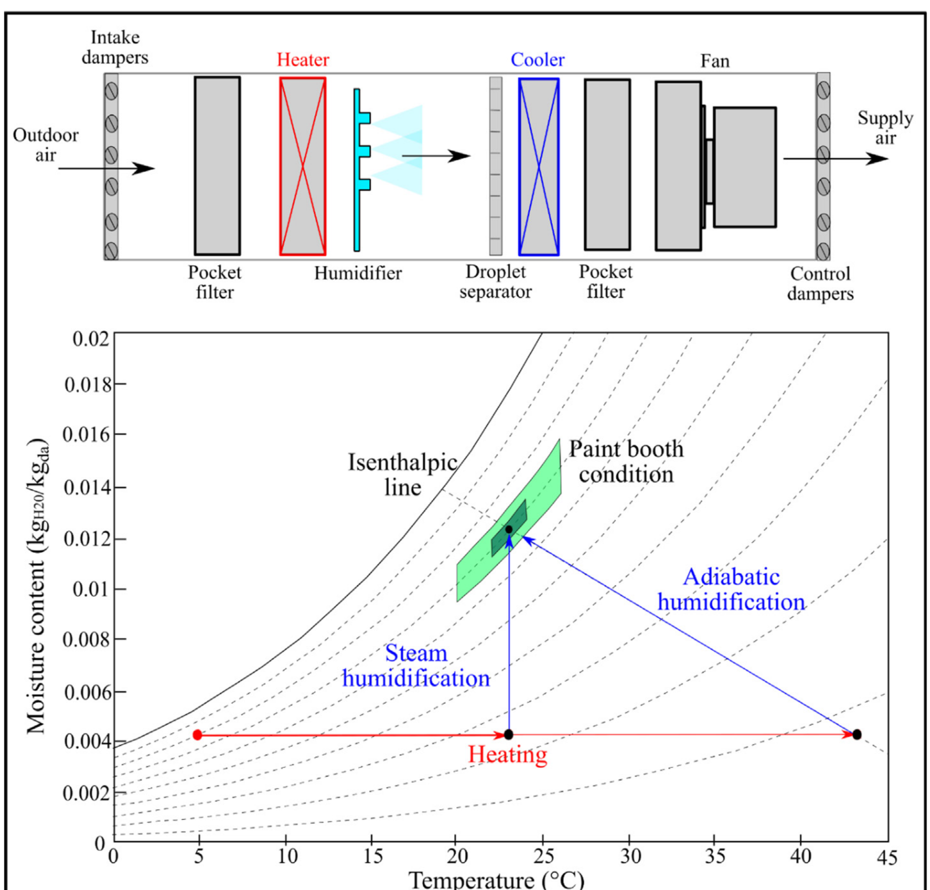


Fig. 17. ASU with 100% outdoor air for air-conditioning paint booth and related psychometric chart, adapted from [43].

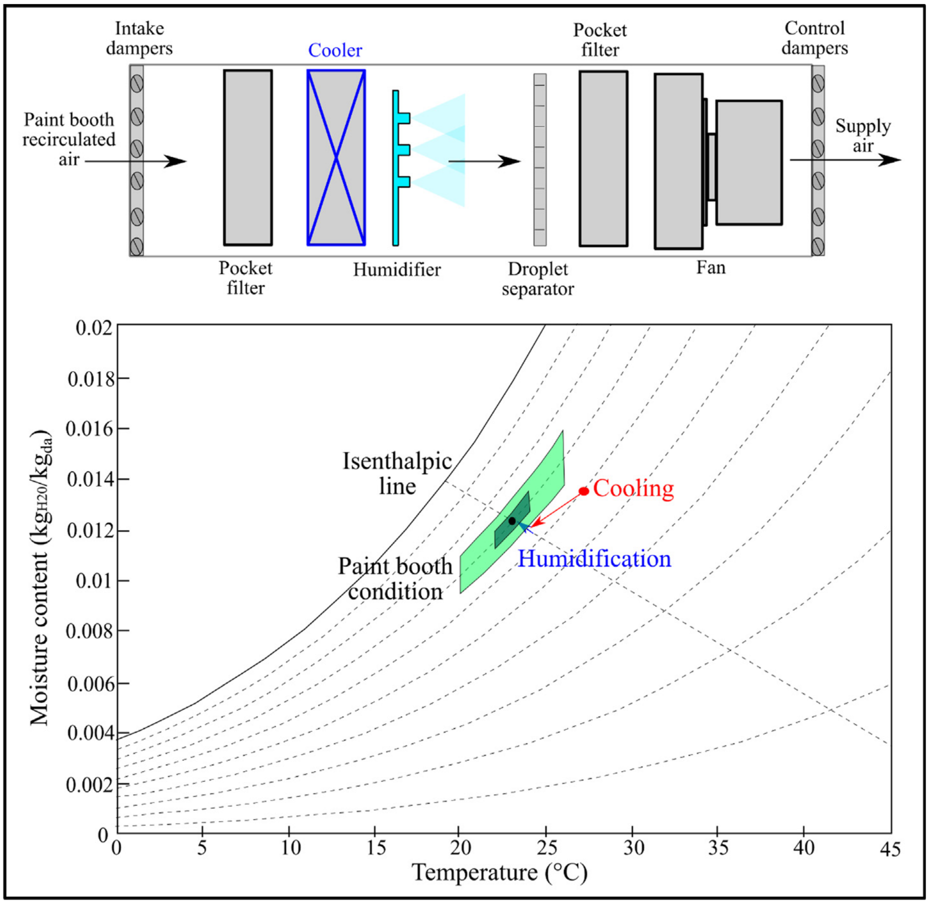


Fig. 18. ARU with recirculated air for air-conditioning in a paint booth and related psychometric chart, adapted from [43].

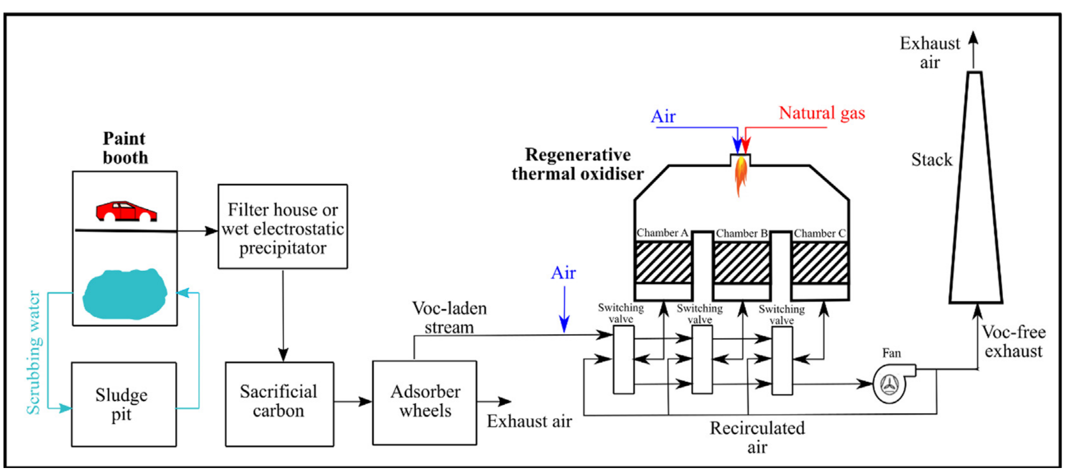


Fig. 19. A wet scrubber, a VOC removal system and a paint booth, adapted from [115].

reused for spraying application. The process is performed by a combination of a cooler and a humidifier. The moisture removal process is performed by the cooler, setting its temperature below the recirculated air dew-point (between 7 and 12 °C) [43]. The dehumidification ability of this process is limited.

Once sprayed, the wet paint must be converted into a dry film. Paint ovens perform this function, consuming a high amount of energy for heating and circulating the air. E-coat, sealing and primer, base- and clear-coat spraying all involve a drying or curing process [23]. Convection ovens are the prevailing choice for paint curing. These ovens use heated air to heat the vehicle substrate, conducting heat and drying the paint [34]. Due to their working principle, convection ovens are effective in dealing with the complex vehicle shape [2]. Basic components of convection ovens are insulated walls and roof, supply ducts and heater boxes, which produce heat by the use of natural gas (alternatively electricity or steam) and supply it to the vehicle body by the means of fans. Energy conservation strategies for paint curing ovens in terms of energy efficiency and heat recovery are further discussed in Sections 3.3.1 and 3.3.2. Proper ventilation and temperature/humidity in curing ovens are indispensable for final product quality. Ineffective ventilation, temperature and humidity control may result in an uneven or ineffective heat-up of the vehicle body during the curing process, leading to a decrease in the physical properties of the paint layer and of the paint quality, characterised by an uneven layer produced [23].

As not all the sprayed paint is deposited on the vehicle, the over-sprayed paint must be collected and removed. The over-sprayed paint collection system is another component in the paint shop which is attributable to intensive energy consumption and environmental impact. Both solvent- and water-based paints have a TE of 40–50%, and therefore 50–60% of the paint is over-sprayed and must be collected for removal [39]. Wet scrubbers are the conventional technology which removes over-sprayed paint by continuously circulating and chemically treated water. The over-sprayed paint and chemical water are flushed into a pan, recovered, handled, and disposed of as paint sludge. After the removal of over-sprayed paint, the exhaust air flows through a filter house or a wet electrostatic precipitator to remove the remaining paint particles. The exhaust air from the wet scrubber system contains VOCs which must be treated before being released into the environment. Fig. 19 shows a wet scrubber, a VOC removal system and a paint booth. The VOC removal system shown is a combination of an adsorber carbon wheel and a thermal oxidiser. This is done to reduce the quantity of air sent to the thermal oxidiser and the fuel consumed for oxidation by up to a factor of 10 [48].

The exhaust air pollution control is hence another highly energy-consuming process in the paint shop. VOCs are the major component of the paint formula for the common solvent-based paints [2]. All the painting processes (E-coat, sealing, primer, base- and clear-coat spraying, drying and curing) release VOCs emissions, e.g. xylene, toluene, ethyl acetate, and butyl acetate [49], which may result in health issues (including irritation to skin, eyes and nose, headaches, dizziness, and cancer) and environmental impact (such as ozone depletion and smog production) [23]. Different strategies have been used by automotive OEMs for VOC removal, as summarised in Table 7.

Other components of primary importance in the paint shop and responsible for remarkable energy consumption are the systems that circulate paint, control temperature and treat water. The paint circulation system delivers paint from the paint mix room to a different point of application, performing the function of paint mixing, filtering and controlling temperature, viscosity and pressure [36]. It is fundamental to control the paint temperature in the paint mix room and during its circulation. To do that, energy for heating and cooling is consumed in the paint mix room.

Painting processes based on dipping (pre-treatment and E-coat) and over-sprayed paint collection with wet scrubber technology consume high quantities of water. Water treatment systems are employed in paint shops to reduce their consumption and recover water from processes, such as pre-treatment and sanding. Main water treatment technologies include reverse osmosis (RO) water plants and electrodialysis [36].

3.3. *Current energy management practice*

3.3.1. *Energy efficiency*

Energy management has been continuously improved by automotive OEMs for reduced energy consumption and enhanced energy savings. Some common energy efficiency strategies are summarised in Table 8.

Evaluation of energy consumption through energy assessment models is key for implementing short-, medium-, and long-term energy reduction and optimisation strategies in the vehicle manufacturing plants [4]. One of the most commonly used energy models is developed by [50,51], which adopts performance-based indicators, known as energy performance indicators (EPIs), to express the energy consumption per vehicle produced (MWh/vehicle). Also, a statistical method combining stochastic frontier analysis (SFA) with data envelopment analysis (DEA) is developed by Oh and Hildreth [21,52] to correlate the effectiveness of energy-saving strategies in vehicle manufacturing plants.

Automotive OEMs have implemented energy, environmental, and quality management systems as recommended by the International Organisation of Standards (ISO), based on the *plan, do, check and act* principle, which results in remarkable savings in energy and material consumption. The ISO Standards related to the automotive sector are as follows:

- ISO 50001 [53] is a standard for energy management system (EMS) used to assist organisations to reach economic savings through better management of the energy sources. The Standard enables organisations to realise a periodically revised and improved policy for better management of energy resources, targets setting and strategies implementation with reduced energy consumption and costs.

Table 7
Characteristics of conventional VOC removal strategies.

VOC removal strategy	Description	Advantage	Disadvantage
Adsorption	VOCs are concentrated by a combination of two wheels ("sacrificial" and adsorber) of carbon or zeolite material. The system must be integrated with a VOC removal system.	• Reduction of the size of the downstream treatment system • If integrated with an oxidation system, reduction of the electricity and fuel consumption will downsize the adsorption system up to a factor of 10	• Possible accumulation of activated carbon • Negative effect of humidity on the process • Possible oxidation of VOCs during adsorption
Absorption	VOCs are captured in a modified version of the over-sprayed paint collection system.	• Possible integration of the system into existing over-sprayed paint collection system	• Possible interference of the chemical solution of the over-sprayed paint collection system with VOCs absorption • Solution not effective
Bio-filtration	VOCs are captured in an aerobic biological reactor for biological degradation.	• High VOC removal	• Feasibility of the biological process limited by the intermittency and discontinuity of the VOC supply
Thermal oxidation	VOCs are removed by oxidation at high temperature.	• Higher VOC removal than absorption-type techniques	• High energy consumption without heat recovery or use of catalytic material
Regenerative thermal oxidiser (RTO)	Ceramic heat-storage modules are used in the combustion chamber of the oxidation process.	• Lower energy consumption due to the heat recovery of the ceramic modules • Most used removal strategy [115]	• High temperature to be reached before starting the oxidation process
Recuperative catalytic oxidiser (RCO)	Catalytic material is used to reduce the temperature required to decompose VOCs in the oxidation process.	• Lower combustion temperature	• Catalytic material expensive

Table 8
Current energy management in the automotive manufacturing plant.

		Energy type	Heat utilisation and recovery
Facility/process/system	General utilities	Thermal/electricityEnergy efficiency	• Combined heat and power (CHP) • Energy management system (EMS)
	Body shop	Thermal	• Heat recovered from metal casting and treatment
	Paint shop	ThermalEnergy efficiency	• Paint booth exhaust air recovered with recuperative heat exchangers, regenerative heat exchangers, and thermal wheels • Paint booth temperature and humidity control with desiccant wheels • Heat recovered from RTO for heating/cooling • Primer-less coating • Three-wet (3-wet) painting • IR/UV paint curing • Dry scrubber • Energy-efficient VOC removal
	Powertrain assembly	Thermal	• Heat recovery from casting and metal treatment.
	Assembly	Mechanical	• Flywheels
Plant utility	Heating, ventilation and air-conditioning (HVAC)	ThermalEnergy efficiencyThermal	• Solar thermal collectors • Heat pumps. • Weekend setback temperature • Better building insulation • Energy-efficient chiller • Solar thermal
	Compressed air systems	Thermal	• Space heating, industrial process heating, drying, etc. • Energy-efficient automatic compressor • Pressure drop minimisation • Pipes and equipment leak reduction • Proper regulator sizing
	Boilers	ThermalEnergy efficiency	• Fuel gas heat recovery for boiler feed-water preheat in an economiser. • Hot condensed water recovery. • Blowdown steam recovery used for space heating and feed-water preheating. • Improved control • Reduced heat losses
	Lighting	Energy efficiency	• Solid state lighting: lighting emitting diodes (LEDs) and radium strips • Efficient control of lighting: daylight use
	Motors	Energy efficiency	• Variable-speed drives
	Welding/stamping	Energy efficiency	• High-efficiency converter/inverter • Rapid freeform sheet metal forming
	Materials handling/tools	Energy efficiency	• Mobile asset scheduling • High-efficiency cog belts

- ISO 14001 [54] is a standard for environmental management systems for the management of an organisation's environmental programme. The Standard enables organisations to minimise water usage and waste production based on design, pollution prevention and end-of-life waste recycling to comply with environmentally-oriented regulations.
- ISO/TS 16949 [55] is a technical specification for the development of a quality management system. This sector-specific quality management standard is developed based on defects reduction to reduce waste and material consumption.

The need for automotive OEMs to develop an energy management strategy aligning with ISO 50001 has led to the introduction of EMS in the automotive sector [4]. As a matter of fact, the development of a consolidated and comprehensive analysis of the energy-related processes in the manufacturing plant is key for energy-optimisation and efficiency of the operations for automotive OEMs [56].

The main energy efficiency strategies employed by automotive OEMs are summarised as follows:

- Combined heat and power (CHP) systems, which have been exploited by automotive OEMs to simultaneously supply electricity, steam and heat, recover the thermal energy that would have otherwise been wasted to produce hot water or steam [57]. The utilisation of CHP technology can result in a reduction of the production costs and of the environmental impact particularly for manufacturing processes with year-round demand for heat, such as the paint shop [4]. The overall efficiency of conventional separation production of electricity and useful thermal energy in an automotive manufacturing plant would increase from 40% to 85% if a CHP system is employed [4]. Additional efficiency and economic savings can be obtained by integrating CHP with absorption cooling technology in a tri-generation system [4].
- Due to the high demand for automation in automotive manufacturing plants, motors are responsible for high electricity consumption, which is even higher if the stamping shop is present on the plant. Variable-speed drives (VSD), which reduce the motor speed by controlling the stator terminal voltage, can significantly curtail the motor energy consumption [4]. General Motors was one of the automotive OEMs which firstly introduced VSD motors at their assembly facility in Fort Wayne to help cooling tower pump systems and fans to operate with more precision [4]. Depending on application, energy saving with VSD motors would range between 7 and 60% [4].
- Conveyors are extensively used in the plant for transport of materials and are responsible for high energy consumption, which can be limited with a well-designed system. Possible identified solutions are the realisation of a conveyor with more efficient components, such as idlers, drive systems, and belts/chains [25]. The use of efficient belts, such as cog belts, could result in a reduction of 2–10% of the motor load [4].
- Efficient lighting can reduce the sensible heat gain in the building, such as daylight utilisation and solid state lighting (light emitting diodes (LEDs) or radium strips), or the use of automatic control systems with light or motion sensors has resulted in reduction of the high energy consumption for lighting [4,21]. In the assembly shop,

approximately 5% of the total energy consumption could be saved by using energy-efficient lighting [4].

- Recovery of mechanical energy with flywheels (which are a mechanical energy storage medium) in the vehicle assembly shop applies a concept very similar to that used in Formula 1 for kinetic energy systems (KERs) [58]. When the body vehicle press stops, the mechanical energy is used to accelerate two flywheels, which will be used in restarting to re-accelerate the body vehicle pressing process. Compared to batteries, an increase of 40% in round-trip efficiency for energy storage with flywheel technology could be obtained [59]. Flywheels find their application in vehicles, where a reduction of 35% in fuel consumption could be achieved [59].
- Energy efficiency strategies for HVAC involve the use of a higher-efficiency electric chiller, solar energy for heating, recovered cooling water from other sources (beneficial effect in terms of water consumption reduction and cooling energy, which could be reduced by up to 20%), setback temperature on the weekend, and energy-efficient technologies that can control temperature and humidity exploiting the heat available on the plant [4,21] (Section 3.3.2).
- The high inefficiency of compressed air systems has made energy efficiency and heat recovery hot topics for automotive OEMs [4]. Alternative energy efficiency strategies have been employed in the past: maintenance of the leaks in pipes (20% of energy savings), minimisation of the pressure drop (5–6% of energy savings), switching on and off according to the production [4,21,24], or radical structural changes in the compressed air system to reach a higher energy efficiency, such as replacing common air-powered tools (pneumatic motors) with electric motors (air-powered motors would consume 7 times more electricity than electric motors), replacing pneumatic suction cups with air actuated magnets, or replacing braided with rubber hoses, which could result in a reduction in the compressed air requirement (ranging from 12.5 to 71.4% in line with production) and the distribution losses [28].
- For steam and hot water boilers, the energy efficiency practices are based on the principles of maintenance, improved control (dampers for flow regulation according to operation) and reduced heat losses [4,22,60]. Previously described, VSDs are also used to increase boiler efficiency by reducing the fan speed. Therefore, VSDs can control the volume flow according to the production and produce electricity savings (up to 60%) [60]. In addition, heat recovery is a hot topic for boilers and further described in Section 3.3.2.
- The welding process is highly automated. Energy efficiency has been achieved through control and the utilisation of more efficient welding/inverter technology (to reduce energy consumption between 10 and 40%) or rapid freeform sheet metal forming (RAFFT) [4,21]. The RAFFT technology, based on the production of sheet metal parts with double-sided incremental forming instead of using stamping and forming dies, is still in the development phase and could reduce energy consumption by 50–90% in comparison to the conventional technology, which requires expensive die design, casting, and extensive operations of machining and assembly [61]. Also, energy consumption during welding can be reduced by supplying a minimum current to the electrode tip [62–63].
- Fig. 2 shows that water consumption per vehicle has been reduced more than 50% since the year 2000 for UK automotive OEMs. This has been obtained through different water conservation strategies, such as utilisation of water recovery technologies (see ultrafiltration unit of the E-coat line in Fig. 11), treatment and use of available water (rainwater and groundwater), installation of flow restriction on the tap water supply line according to requirement, leaks elimination, etc. [64].

To realise a less complex painting process with less material consumption at a lower cost whilst ensuring quality of the final product, energy efficiency strategies have been developed in line with painting material (where paint with less VOC emission is preferable) and process (wet-on-wet painting process, oven temperature reduction, etc.) [9].

The main innovations for the painting process as shown in Fig. 20 are further described, as follows:

- Through a reformulation of the paint composition and of the paint drying process, automotive OEMs managed to eliminate the primer coat deposition and curing process, resulting in a reduction in the paint shop's capital cost and energy consumption due to the absence of the primer paint booth and oven and of the associated equipment (mixing room, paint circulation system, etc.). An actuator is added to the base coat layer so that it adopts the function of primer surfacer of chip resistance and UV barrier for the E-coat layer [2]. It is estimated that savings of 30% of space and capital cost are achievable with this strategy [2]. Additional savings are possible by avoiding the sanding process after primer deposition [2].
- As previously said, the reduction of painting process complexity is the top strategy for energy consumption reduction. For this reason, the realisation of a painting process able to paint on wet paint has been seen by automotive OEMs as the most effective strategy, which can eliminate the curing process between the spraying of the two paint layers and reduce its energy consumption and VOC and CO_2 emissions. More recently, an innovative process introduced by Ford and Mazda based on the realisation of wet-on-wet-on-wet (3-wet) painting was studied and realised [9]. In the process shown in Fig. 20, only one curing phase is performed after the deposition of the three layers of paint. It is estimated that the time of painting operation and the size of the whole paint shop could be halved by the introduction of this technology while continuing to ensure a final durable and good quality product [9]. A representation of the beneficial effects in terms of energy consumption and emissions of these innovative strategies of the painting process is shown in Fig. 21.

As indicated in Fig. 21, the transition from solvent- to water-based paint would result in a beneficial effect in terms of VOC emissions, but the highest energy consumption required for paint drying would lead to in higher CO_2 emissions. The 3-wet technology shows the best environmental performance in terms of energy consumption, CO_2 and VOC emissions. Fig. 21 also shows the environmental impact of the innovative painting process developed by Mazda in the 2010s i.e. aqua-tech paint system [65]. The technology proved that remarkable environmental and economic benefits can be obtained through the realisation of a more functional process based on the outdoor air control strategy and the use of water-based paint, which reduces CO_2 and VOC emissions, respectively.

Modifications to the oven characteristics or design have also been identified as feasible strategies for energy reduction. Despotovic et al. [66] developed a model for the study of the variables affecting the operating parameters of the system, such as air and vehicle body temperature, and the realisation of curing ovens with better performance. Given the variability of the vehicle production process, energy efficiency strategies identified for curing ovens are the reduction of the air flow rate supplied to the oven during downtime [24] or according to the required production [67]. Through effective management of the air flow rate in the ovens, significant economic saving in terms of thermal and electric energy can be obtained by avoiding heating and reducing the fan speed [26]. The development of Industry 4.0 will also be a game-changer for the sector, where wireless technology would enable the production process to work as ideally as possible by recognising possible downtime of the production process and idle cycles, and consequently reducing the oven air flow rate. The importance of Industry 4.0 for the future of the automotive sector is further described in Section 4.

Alternative curing techniques, such as infrared (IR) and ultraviolet (UV) curing, have been studied as an energy-efficient substitute for conventional curing techniques [4]. IR curing is a technological

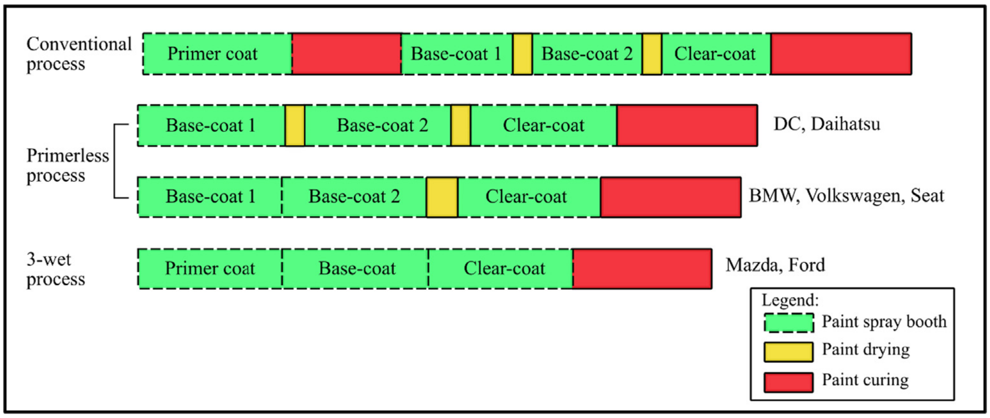


Fig. 20. Evolution of the painting process, adapted from [2].

solution currently used for energy reduction of the curing process. This is due to its ability to speed up the curing process, resulting in a paint booth size reduction and increased productivity [4]. UV curing also reduces energy consumed in the painting process, due to the lower temperature and time required by the process [2]. UV curing is currently used for painting of automotive plastic parts [4]. However, the higher energy cost of UV curing partially offsets the process advantages compared to conventional curing, making IR curing more attractive as an energy-efficient strategy for oven curing which could reduce energy consumption by 50% [4]. A hybrid technological solution, using the IR oven for the heat-up zone and the convection oven for the hold-on zone is considered as one of the best strategies for quality and energy consumption reduction in the clear-coat curing process [36].

For dipping processes, such as pre-treatment and E-coat, the roll over dip (RO-Dip) technology has significantly limited the energy consumption and environmental burdens of the manufacturing process. Through the use of conveyors that allow to tilt, rotate and dip the body vehicle, benefits such as higher painting quality, increased line capacity, shorter line length, less wastewater and sludge and reduced bath volumes (i.e. lower energy consumption for pumping) are obtained. Approximately 10 and 20% of the costs for E-coat and pre-treatment lines with RO-Dip technology, respectively, could be saved [68].

For the collection of the over-sprayed paint in the paint booth, a "dry" scrubber is identified as a key milestone for energy efficiency and sustainability. Akuafah et al. [9] pointed out that this technology is gaining more interest in replacing the conventional "wet" scrubber due to its potential to significantly reduce energy consumption, CO_2 and particulate emissions, and water consumption in spray booth. The "dry" scrubber technology utilises a plastic filter protected by a layer of $CaCO_3$ with the ability to capture the over-sprayed paint particles. The process produces solid waste, similar to limestone, which is collected, recycled and sold, presenting an economic return for automotive OEMs. Alternative "dry" over-sprayed paint removal systems involve the use of a set of filters made of easily replaceable cardboards, such as in the EcoDry scrubber technology introduced by Dürr [69] and the use of high voltage instead of filters for the separation process of over-sprayed paint [70]. An up to 60 and 80% reduction in energy and water consumption respectively was reported by the manufacturer [69].

Energy efficiency strategies for VOC removal involves the use of a more energy-efficient combustion process [71]. It is claimed that the use of non-thermal plasma coupled with catalysts is advantageous, given the ability of the technology to operate under more favourable conditions, such as low temperature and atmospheric pressure. Alternative energy efficiency strategies for VOC removal involve re-thinking the VOCs exhaust stream as a resource, given its energy content that could be somewhat exploited in the paint shop. In the recent period, the possible utilisation of absorbed VOCs to drive a solid-oxide fuel cell (SOFC) and produce electricity has been investigated by Ford Company [48]. A lower cost of SOFCs could make the technology more attractive for automotive OEMs.

3.3.2. Heat recovery

Thermal energy recovery, management and utilisation is a central strategy to leverage the present excess heat and realise a more efficient manufacturing process. Common sources of waste heat for the automotive manufacturing process include high-, medium- and low-temperature industrial systems for heating (furnaces, kilns, ovens, dryers and boilers) and their exhaust gases, compressed air, ventilation and refrigeration. Potential waste heat sources and possible recovery applications are classified by temperature range and summarised in

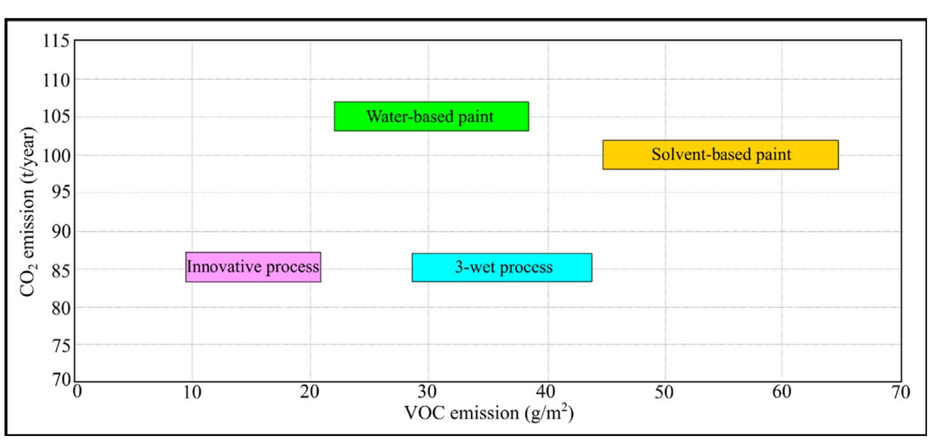


Fig. 21. CO_2 and VOC emissions of different painting processes, adapted from [65].

Table 9
Classification and description of waste heat recovery sources and potential application in automotive manufacturing plants.

Process/system	Use	T (°C)	Potential recovery	HE*
Metal casting and treatment	• Engine and transmission manufacturing • Aluminium casting	430–750 [75]	• Recuperator for combustion air preheating • Waste heat recovered from metal casting can be absorbed by raw materials during production	G/GS/S
Boiler exhaust	• Steam production	230–300 [60]	• Economiser for boiler feed-water preheating • Blowdown hot water or steam recovery • Combustion air preheating with heat wheel	G/LL/G, L/LG/G
RTO system	• Thermal oxidation VOCs present in the exhaust air	170–200**	• Hot water production for heating (space or process) and cooling (absorption cooling) • Combustion air preheating with heat wheel	G/LG/G
Paint curing oven	• Paint curing after deposition	130–180 [2]	• Hot water production for heating (space or process) and cooling (absorption cooling) • Combustion air preheating with heat wheel • Air heating for solid desiccant cooling	G/LG/GG/G
Flash-off drying booth	• Partial paint drying	70–90 [2]	• Warm water production for liquid desiccant, absorption cooling or heat pumps • Air heating for space heating and solid desiccant cooling	G/LG/G
Air compressor	• Different applications	40–50 [88]	• Warm water for space heating, liquid desiccant and heat pumps • Air preheating for space heating	L/LL/G
Chilled water	• Air-conditioning • Paint cooling process	40–45 [89]	• Warm water for space heating, liquid desiccant and heat pumps • Air preheating for space heating	L/LL/G
Exhaust ventilation air	• Air-conditioning for building and the painting process	23–26 [43]	• Air preheating or precooling	G/G

* Heat Exchange (HE): Gas to Gas (G/G), Solid to Solid (S/S), Liquid to Gas (L/G), Liquid to Liquid (L/L), and Gas to Liquid (G/L).
** Data input from by a manufacture in the UK.

Table 9. As reported by [72], remarkable energetic, economic and environmental benefits can be obtained by the realisation of an on-site heat recovery network to considerably reduce the cost of the heating, cooling, and paint drying process.

Different heat recovery devices can be used in the automotive manufacturing plant including various heat exchangers, e.g. recuperative (radiation, convective, or a combination), regenerative (rotary wheel, thermal or desiccant), passive heat preheaters and heat pumps [32]. The choice of the heat recovery device will depend on the temperature range, the intended application (cooling or heating) and the required working fluid (air, water or thermal fluid).

Metal casting and treatment processes (taking place in a press shop and during manufacturing of engine, transmission, etc.) include all the metalworking operations involved in the alteration of the physical properties of metals for a specific application. Given the high temperature required by these metalworking processes, different heat recovery strategies can be performed with economics savings. However, the temperature range of these processes (between 430 and 750 °C) limits the use to dedicated heat exchangers only, which prevents the thermal expansion of the material, such as recuperators (radiation and convection) and ceramic heat wheels [73].

A viable alternative solution for energy savings and environmental benefits is recovering energy from bulk material manufacture [20]. An example is the utilisation of waste heat for scrap preheating after the casting process, as waste heat is abundant when the molten metal solidifies and cools down. A 5% heat recovery efficiency is achievable. This is of interest to the automotive manufacturers considering the high number of casting operations performed worldwide [74].

Boilers have been extensively used in automotive manufacturing plants for steam and hot water generation. Waste heat from boilers can be utilised by (i) recovering the heat content of the exhaust flue gas, (ii) recovering the heat from the boiler blowdown water, (iii) preheating the combustion air (less used), or (iv) a combination of (i)–(iii) [4]. Blowdown water is the water that must be continuously replaced from the boiler to avoid fouling and build-up of solids after steam production. In relation to boilers, the most commonly used heat recovery strategy is the employment of economisers to preheat feed-water. It was reported that boilers with a capacity higher than 7300 kW would be supplemented by economisers [75]. The main drawback of the process is the possible condensation of sulphuric acid when the temperature on the heat exchanger's walls is lower than the acid dew-point. A minimum temperature of 120–150 °C is maintained to prevent condensation of water in the exhaust gas and deposition of corrosive substances which will result in malfunctioning [75]. The use of condensing economisers increases the heat recovery ability of the process, enabling the recovery of latent heat from water condensation at a temperature lower than 100 °C. Different condensing economisers are available commercially, such as deep economisers (exhaust temperature ranging between 65 and 71 °C) and indirect or direct contact condensation recovery systems (exhaust temperature ranging between 38 and 43 °C) [75]. However, the high capital cost of these heat exchangers limits their worldwide use. It is estimated that up to 80% of the blowdown water heat can be recovered by using flash steam recovery vessels and/or heat exchangers [60].

Diesel-powered generators are largely used in automotive manufacturing plants to ensure continuous production during power failure. The use of the heat produced by these generators for electricity production with organic Rankine cycle (ORC) technology was investigated by [76] which reported a saving of up to 10% in fuel consumption with the technology and an overall thermal efficiency up to 60–90% for dual loop ORC systems. Apart from generator heat recovery, ORC technology can be applied to recover waste heat produced by vehicles. Similarly, thermo-electrical modules (TEMs) can be applied for cooling and power generation and their use for vehicle application was investigated due to high reliability, low noise, no operating or moving parts, etc. by [77,78]. In the cooling configuration, the exhaust heat from the vehicle produces cooling through Peltier effect that can be used as vehicle mini-refrigerator or air-conditioner [77]. In the generation configuration, the exhaust heat from the engine is used to produce electricity through Seebeck effect for lighting and auxiliaries. The use of TEMs would allow for the use of smaller alternators leading to reductions in weight and fuel consumption [78].

To recover waste heat of the medium- and low-temperature ranges in the manufacturing plant, regenerative heat exchangers (thermal or desiccant) and passive air preheaters (plate-type or heat pipes) are used to produce hot air [75]. Due to their ability to recover not just heat but also moisture and considering the importance of moisture control on site, the use of regenerative heat exchangers with hygroscopic material (solid desiccant wheel) is particularly attractive for the application in the paint shop.

Hot water production using waste heat from thermal oxidisers, ovens and dryers is another heat recovery strategy with economic benefits in the medium temperature range. The hot water could be subsequently used for space heating, process heating or cooling with thermally-driven technology (absorption or solid desiccant cooling), which will reduce natural gas and electricity consumption of the automotive plant [79,80]. Additional applications include the pre-treatment painting and oil conservation process [81]. The feasibility of recovering waste heat from ovens, dryers and oxidiser must be evaluated case by case, depending on the paint and solvent used in the painting process, and the available waste heat content [34]. This is due to the fact that the streams in these systems are VOC-laden and cannot be used for hot water production without heat exchangers, resulting in additional costs [34]. As previously described, the maximum recoverable heat is limited by possible condensation at a temperature lower than the dew-point of the acid. Due to the low content of VOC in the RTO stack exhaust, two strategies have been identified as viable and economic advantageous:

- Superheated water at 15 bar is produced by recovering waste heat from the RTO heat stack and used in the ASU which delivers air to the paint booth. This reduces natural gas consumption required by the process, as evidenced by [82] which reported that a reduction of 16% in the energy consumption was achievable. The described heat recovery strategy is shown in Fig. 22.
- Cooling production with absorption cooling technology: hot water (or other thermal fluid) is produced by recovering heat from the RTO stack and used to drive a single- or double-effect system, depending on the quality of the available heat. In the single-effect system shown in Fig. 23, the hot water produced by the RTO stack is used in the generator to evaporate the refrigerant (water) from the solution (usually lithium bromide, LiBr). Absorption cooling systems can produce a cooling effect by exploiting low-temperature waste heat, reducing the electricity consumption in the automotive manufacturing plant. It is estimated that approximately 10% of the plant cooling requirement could be provided by absorption cooling driven by RTO heat recovery. The high capital cost of the technology limits the economic benefits of the process. However, this heat recovery strategy is proven as economically advantageous in the design phase of a new paint shop, while it is limited in retrofitting.

An alternative strategy for the exploitation of low-temperature heat sources is the use of heat pumps in the automotive plant. This technology has gained interest due to its ability to efficiently use waste heat and provide simultaneous heating and cooling, which is required by the painting process [83,84]. Heat pumps are able to upgrade the available waste heat to produce the required temperature for a process. Depending on the configuration design, the technology is able to provide heat at a higher temperature or cooling [75]. Heat pumps can find different applications in the paint shop, such as washing with hot water, pre-treatment/E-coat, flash-off, as well as conditioning the supply air [83]. Fig. 24 shows an example of using heat pumps to supply air to the paint booth, which reported an energy consumption reduction of 49% compared to conventional boiler heating.

The importance of controlling the temperature and humidity of the supply air during the water- and powder-based painting process has made heat pumps particularly appealing. The ability of heat pumps to evaporate the water content in the paint at low temperature and humidity eliminates the cooling process after the flash-off process, and consequently leads to economic savings [85]. For large commercialisation of heat pumps in the automotive industry, the development of high temperature heat pumps (HTHP) is required. Using scroll compressors and internal heat exchangers, the HPHT developed by [86] can be driven by low-temperature heat (60–80 °C) which was upgraded up to 140 °C. The potential of the technology in the automotive industry is significant since it could be exploited for steam or pressurised water production, which will decarbonise the manufacturing process. In addition, the integration of this HTHP with CHP is envisaged to be effective for automotive manufacturing as electricity and heating are required all year round.

As the most significant energy consumer during vehicle manufacturing, the paint shop can achieve remarkable economic benefits by recovering low-temperature waste energy on-site, as follows:

- The exhaust air from the paint booth is recovered to precondition the outdoor air (i.e. heating or cooling according to the season). As the process consumes high energy, recovering exhaust heat from ASUs for heating up the air in winter and cooling it down in summer is of the main strategies used to reduce the energy consumption. A heat recovery efficiency of 45% was reported for the heat exchanger [87]. Contaminants such as oil mist, particulates, and pollutants in the exhaust air must be filtered or removed before heat recovery

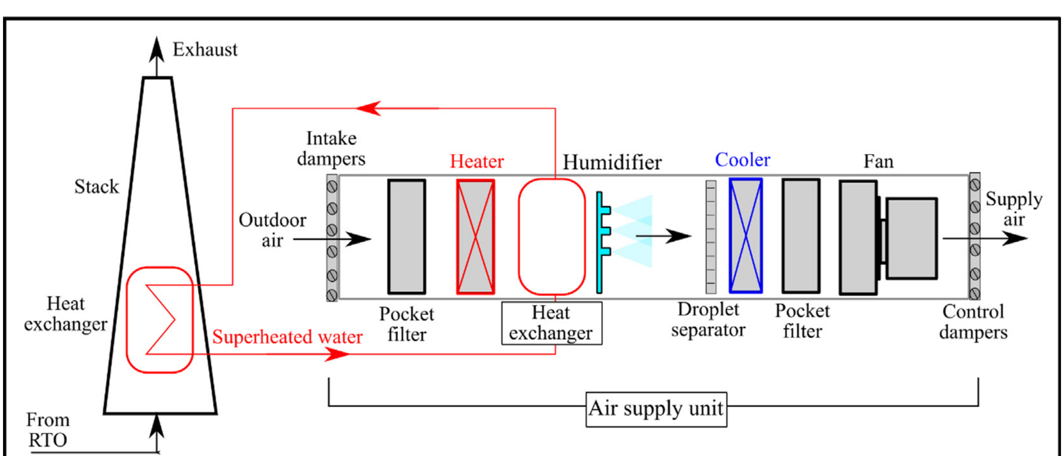


Fig. 22. RTO stack heat recovery for air supply to the paint booth, adapted from [82].

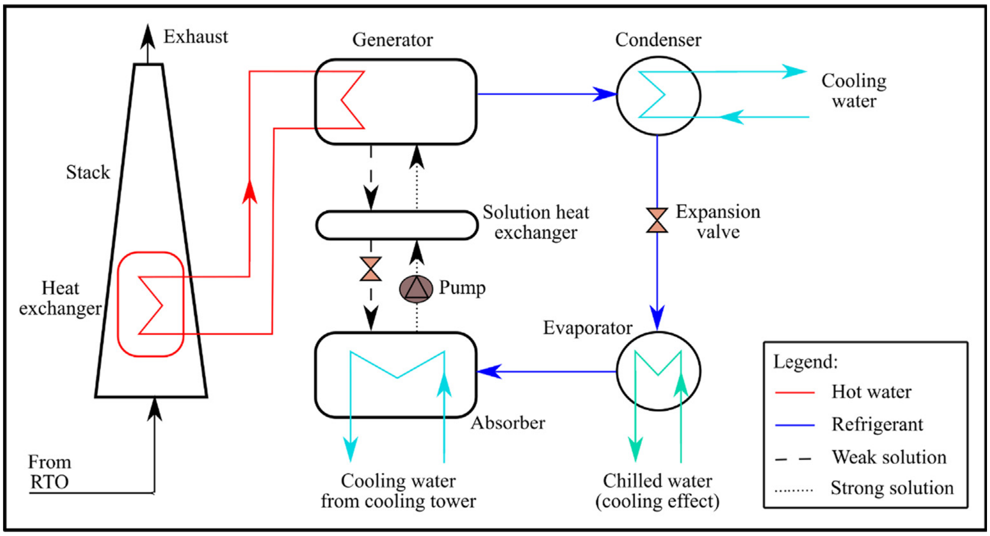


Fig. 23. RTO stack heat recovery for cooling production with a single-effect absorption chiller.

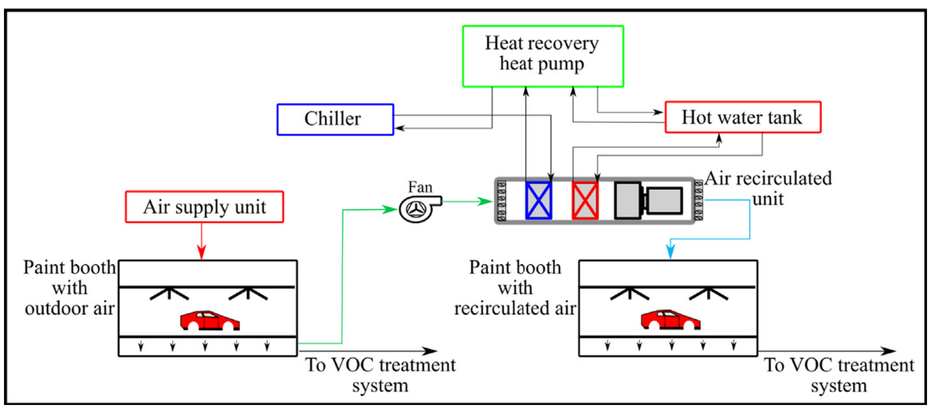


Fig. 24. Paint booth with outdoor and recirculated air and heat recovery heat pump, adapted from [83].

[32]. Fig. 25 shows an example of a cross-flow heat exchanger (recuperator) applied in a paint booth [87].

- Air produced after compression is hot (temperature between 80 and 170 °C) [88]. Before being distributed and used, this compressed air must be cooled with air or water. The heat recovered from cooling the compressed air (ranging between 45 and 50 °C) can be used for different applications, such as space heating, hot water heating, boiler's feed-water, make-up air preheating, process heating, drying, and to supply heat to heat pumps [4,88].
- Chilled water is largely used in the paint shop, particularly during paint booth operations. Utilising the heat released by the condenser of the chilled water system presents a potential heat recovery strategy [89]. Depending on the system configuration (air- or water-cooled), this waste heat can be used for space heating (mainly with an air-cooled system where the hot air is ducted to the required space), process heating and HVAC (with water-cooled systems).

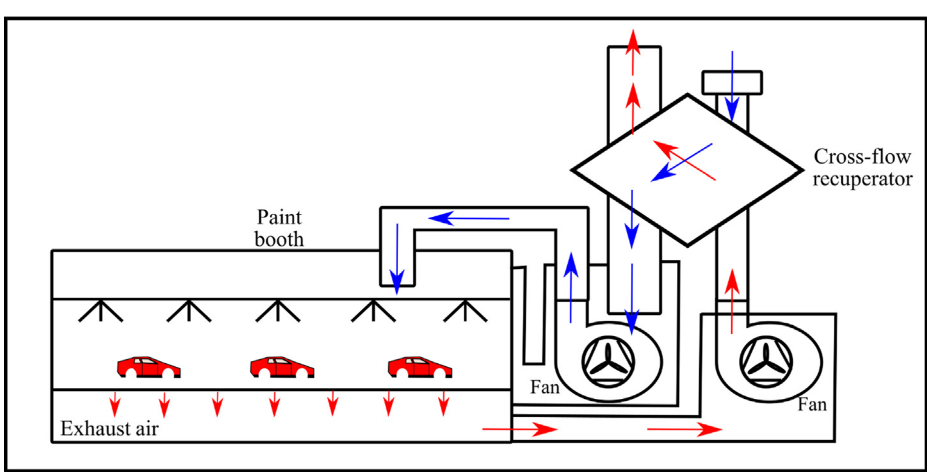


Fig. 25. A paint booth with a cross-flow heat recovery unit, adapted from [116].

Table 10
Utilisation of renewable energies in automotive manufacturing plants.

Renewable energy	Description	Example of manufacturers
Solar photovoltaic	• Conversion of solar irradiance into electricity using semiconducting materials	• Seat, Martorell facility: Biggest photovoltaic plant for automotive manufacturing (8 MW) [183] • Nissan, Sunderland facility: 4.75 MW solar plant
Solar thermal	• Conversion of solar irradiance into hot water production, used for space heating, paint booth, etc.	• Dürr, Eco + Paintshop [91]
Wind	• Electricity produced by capture of wind power through wind towers and turbines	• Nissan Mexico, Sunderland (6.6 MW) and Aguascalientes facility • BMW, Leipzig facility: Production of 20% of the energy required with wind turbine plant [184] • Ford, Dagenham facility: 2 turbines with a combined capacity of 3.6 MW.
Hydroelectric	• Low-carbon electricity source that could be used in the manufacturing process. Depending on the location and water availability	• Volkswagen, Chattanooga • BMW, Moses Lake facility: Hydroelectric energy for the production of carbon fibres
Geothermal	• Mostly used for applications where heat is required. Depending on the location and heat availability	• Audi, Gyor: 60–70% of the plant requirements is obtained by geothermal heat (82 GWh/y produced)
Landfill gas	• Mix of different gases (approximately 50–60% methane and 40–50% carbon dioxide) created by the action of microorganisms within a landfill and used as fuel replacement. More reliable and constant than other renewable energy sources	• GM, 4 facilities in the USA: Use of landfill gas as energy source of power plant boilers • Nissan Mexico, Aguascalientes facility • BMW, Spartanburg facility: Energy production from its landfill gas-to-energy program. Under study the landfill gas-to-hydrogen process to power fuel cell vehicles

Heat recovery from a water-cooled chilled water system can also be employed to drive heat pumps [89].

Currently, low-temperature waste heat is available abundantly but has not been efficiently exploited in the automotive plant. The ideas of exploiting heat recovered from compressed air or chilled water systems for the regeneration of a liquid desiccant solution (requiring heat with temperature ranging between 45 and 60 °C) [90] and employing technology to control the temperature and humidity of outdoor and recirculated air before supplying to the paint booth are contemporary subjects that will be further studied.

3.3.3. *Use of renewable energy*

In line with the high demand for electricity and heat during automotive manufacturing, automotive OEMs have started to employ various renewable energy alternatives including low-carbon energy sources [21,57] as summarised in Table 10.

An example of the integration of renewable energy in the paint shop is shown in Fig. 26, where the solar thermal technology developed by Dürr is able to effectively lower the energy consumed by the process [91].

The system exploits Fresnel collectors and is able to produce superheated water that can be as hot as 400 °C [91]. The superheated water is delivered to the ovens for the paint curing process. Considering different process temperatures in the plant, a heat cascade strategy is established: (i) the exhaust air of the ovens is sent to the RTO where it is oxidised to burn the VOCs present, (ii) the RTO stack heat is recovered for hot water production used for intermediate ovens, and (iii) the remaining exhaust heat is used for preheating fresh air and for conditioning paint booth supply air.

A more innovative technological solution combining micro gas turbine technology with a linear concentrating Fresnel collector has been developed by Dürr for efficient generation of process heat and electric power, as shown in Fig. 27 [92].

By the combination of these two technologies, Dürr managed to ensure continuous production of heat and electricity, independent of

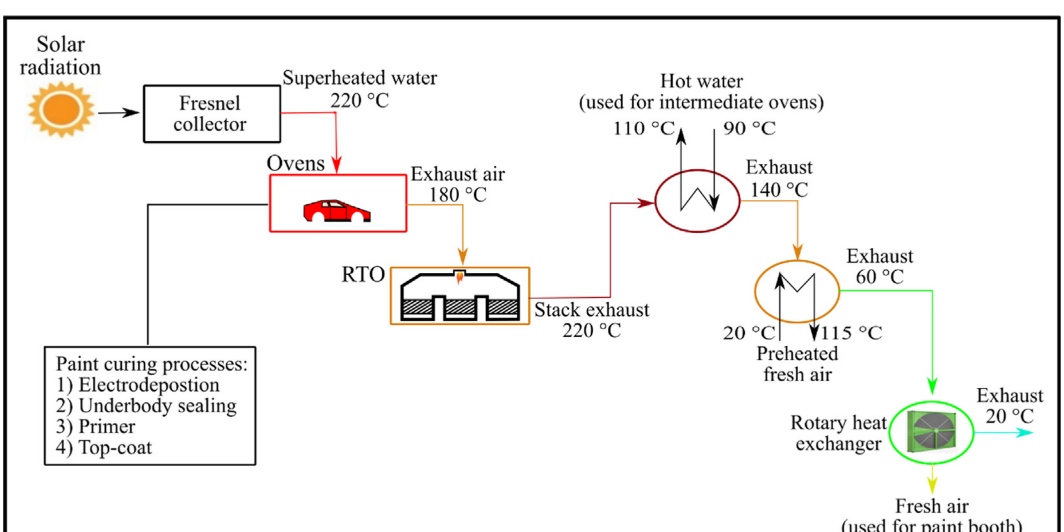


Fig. 26. Heat cascades with solar energy and heat recovery for a paint shop, adapted from [91].

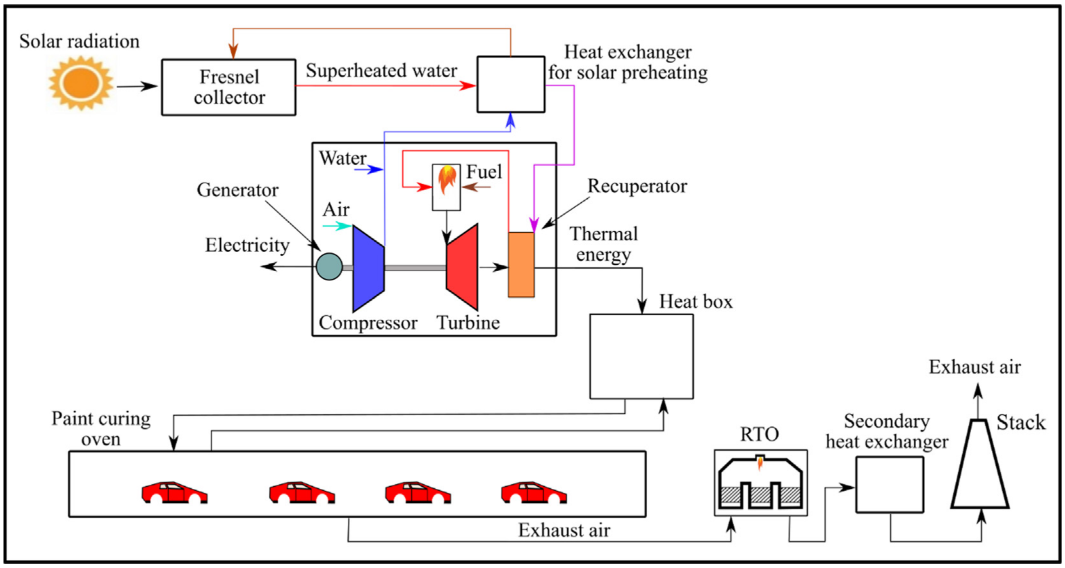


Fig. 27. Oven heating with CHP and a Fresnel collector for painting process, adapted from [92].

outdoor air condition. While electricity is used for different applications through the plant, the waste heat produced by the gas turbine of the CHP system is used for curing the paint in the oven. The system reduces up to 35% the fuel combustion and increases the overall efficiency of the system beyond 90% [92]. Fig. 27 also shows optional secondary heat recovery from the RTO, which could be used for absorption cooling or heating of the ASU of the paint booth, as previously described.

4. Moving towards low carbon automotive sector

Since the 1990s, automotive OEMs have established alliances among themselves and with governments to work towards innovation and sustainability [7]. For instance, the Automotive Sector Deal was established in 2018 between the UK government and automotive manufacturers to review annually and identify business opportunities for realising a low-carbon economy for the sector [93]. The identified medium- and long-term strategies by automotive OEMs and the proposed technology and timeline are represented in Fig. 28 and Fig. 29.

The realisation of a sustainable low-carbon sector passes through a combination of sustainable vehicle manufacturing and sustainable mobility [7]. The industry must modify its supply chain in line with the development of more environmentally-friendly vehicles in the near future. The energy consumed in manufacturing these alternative vehicles must not offset the benefits gained in driving them. The sector is envisaged to produce more advanced, cleaner, safer, and more comfortable vehicles with the lowest possible energy consumption and environmental impact. To adapt to the new challenges, advances in technology and automotive manufacturing processes including high-volume production of transmission systems for electric vehicles, electric motors, energy storage systems (batteries, capacitors, etc.), electronics for control as well as assembly processes are required [20].

4.1. Low-carbon driving

The limit for CO_2 emissions, which is currently defined as 130 g CO_2/km, has to be reduced to 95 g/km by 2020 and 75 g/km by 2025 [94]. The average CO_2 emission level of new vehicles defines CO_2 emitted by vehicles per 1 km of travel distance, depending on the mass of the vehicle, which is determined by an equation with variable correction factors [94–95], as follows:

$$Specific\ \ emission_{CO_2} = S + a * (m - m_0) \tag{1}$$

where Specific emission_{CO2} is the maximum allowable emission per 1 km of travel distance (g CO_2/km), S is a correction factor, which is the limit for CO_2 emissions, a is another correction factor, which is

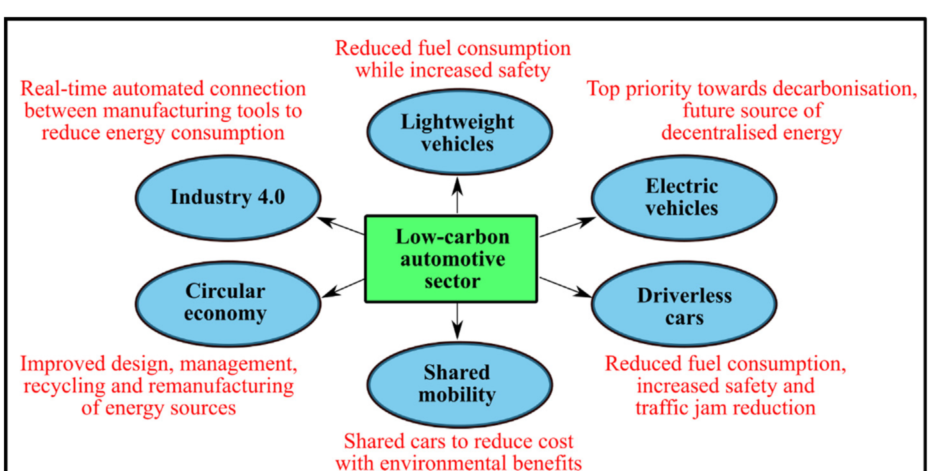


Fig.28. Strategies towards a low-carbon automotive sector as identified by automotive OEMs.

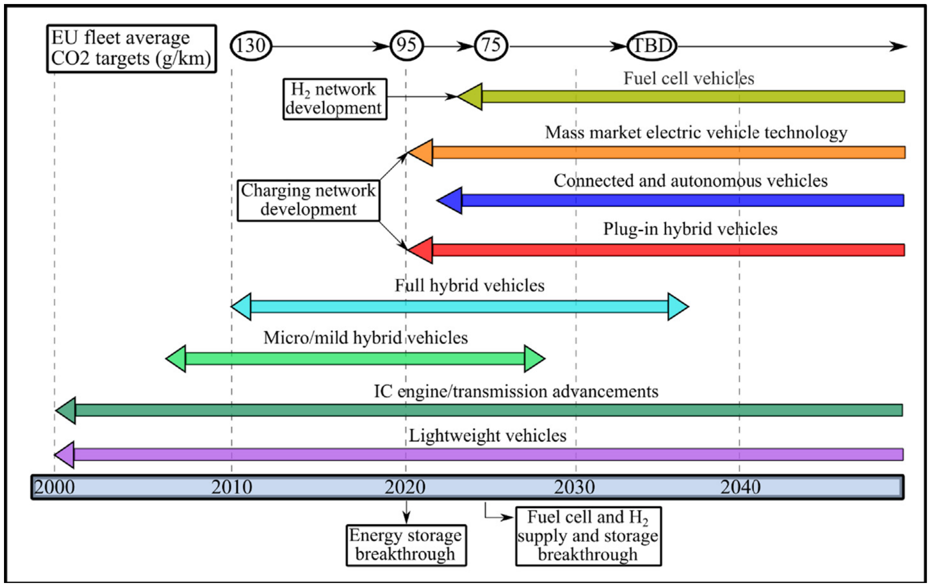


Fig. 29. Vehicle technology and the timeline proposed for moving towards sustainability, adapted from [105].

currently defined as 0.0457 g/km * kg, m is the curb vehicle mass (kg) and m_0 is the reference mass, currently 1.372 kg.

Fuel efficiency is hence one of the top priorities towards sustainable automotive industry. Apart from aerodynamics and rolling improvement, the production of lightweight vehicles has identified as the main strategy to boost fuel efficiency [96]. As a matter of fact, lightweight vehicles release less exhaust because of their smaller propulsion packages and lower energy consumption [97]. The effect of the reduction of the vehicle's weight on the fuel consumption is expressed by the following equation adapted from [5]:

$$FE = 2,\,106.45\left(\frac{m}{2.205}\right)^{-0.463} \tag{2}$$

where FE is the fuel efficiency expressed in the distance travelled per litre of fuel consumption (km/l). The equation indicates that a reduction of 10% in the weight would increase FE by approximately 5% which is equivalent to a reduction in the fuel consumption of 5%. As such, a remarkable weight reduction is required to significantly reduce the fuel consumption of vehicles [98].

4.2. Low-carbon manufacturing materials

Whilst steel and iron are conventional materials used for vehicle BIW, research for lightweight vehicles will stimulate substantial modification in materials used for the vehicle body [99]. In the future, the material will be a mix of aluminium, magnesium, high-strength steel, carbon fibre, plastic (at a higher utilisation rate), etc. with a higher strength-to-weight ratio, thereby reducing the vehicle weight while improving its performance [5,97]. Nevertheless, the production process of these lightweight materials affects the sustainability of the whole system from a broader perspective. The primary energy consumption for aluminium, magnesium and carbon fibre production and recycling is 26–249 MJ/kg, 39–360 MJ/kg and 168–754 MJ/kg, respectively, which are higher than that of steel, i.e. 12–54 MJ/kg [100]. Therefore, whether lightweight vehicles can reduce the energy consumption and environmental impact of the automotive sector is closely related to how the components are manufactured. An example is using hydroelectric energy in producing carbon fibres as previously reported in Table 10. Fig. 30 shows the envisaged changes in materials used for BIW vehicles, indicating an increase of aluminium, magnesium, carbon fibre, and high-strength steel to replace mild steel in the future.

4.3. Low-carbon vehicles

Electric vehicles are seen by automotive OEMs as the optimal strategy for better management of the energy sources and reduction of vehicles' emissions, environmental impact and noise [101]. Development and commercialisation of electric vehicles, such as battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell electric vehicles (FCEVs), is a primary short-, medium-, and long-term focus for automotive OEMs. A higher market share for the electric vehicle sector is expected for the future, which would increase from 3.1 million vehicles on the road in 2017 to 125–225 million vehicles by 2030 [101]. Amongst the innovative technologies for the realisation of hybrid electric vehicles powertrain, free-piston engines are of interest for automotive OEMs [102]. These engines, with no crankshaft present, have a lower frictional loss, faster expansion stroke, more efficient production and reduced emissions.

Currently, limited charging infrastructure, expensive battery cost and low performance are the main obstacles hindering the commercial use of electric vehicles worldwide [103,104]. The role of governments is hence fundamental for future development. For instance, FCEVs are seen as the very promising technology for low-carbon transport [104]. However, the current high cost of fuel cells, H_2 storage and distribution requires financial incentives for their mass market development [105].

Similarly, the future success of EVs and FCEVs is strictly connected to the development of an electric charging and H_2 supply infrastructure [105]. The realisation of an electric charging and H_2 infrastructure which can supply fuel to EVs and FCEVs must be supported by investments and collaborations among automotive OEMs, local and national authorities [105]. From an environmental viewpoint, the coupling of electric vehicle production and use with low-carbon energy sources, such as biofuels or natural gas, is worth-investigating [100].

The realisation of Connected and Autonomous Vehicles (CAVs) is another of the top future strategies of automotive OEMs. It is expected that these driverless cars will be on UK roads by 2021 [93]. Through the utilisation of communication, such as Vehicle-to-Infrastructure (V2I), Vehicle-to-Vehicle (V2V), and Vehicle-to-Device (V2D), and automated systems, CAVs have the potential to result in several benefits, such as improved driving safety, traffic efficiency, and economic savings in terms of fuel consumption and reduced insurance cost [96]. As less safety equipment is required by these vehicles, the traffic incident control function provided by CAVs will allow automotive OEMs to reduce the weight of future vehicles [96]. As shared vehicles are also seen

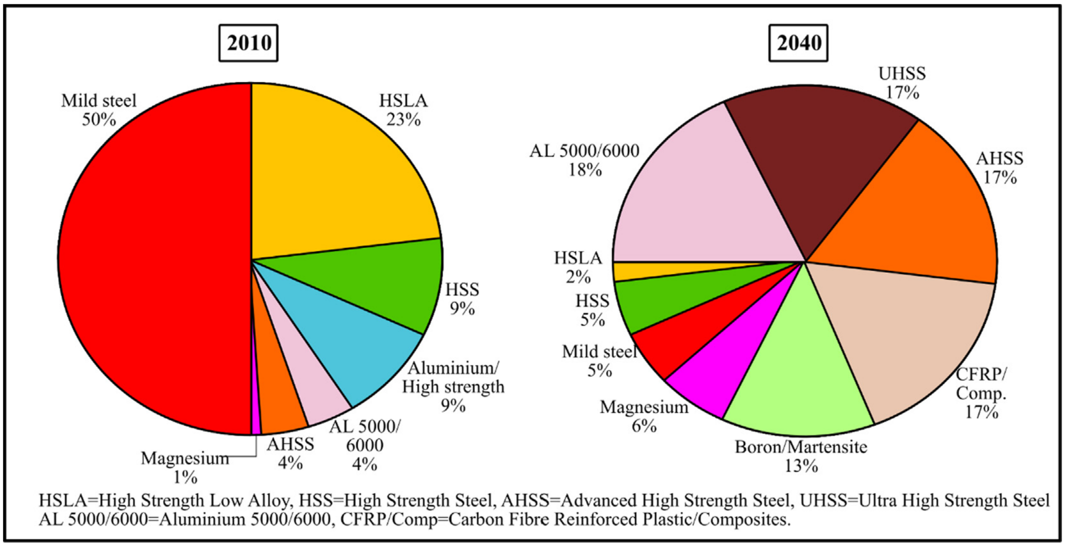


Fig. 30. Materials mix for current (2010) and future (2040) BIW, adapted from [97].

as a step towards the low-carbon sector, sustainable vehicles in the future are envisaged to be automated, connected, electric, and shared (ACES) [106].

4.4. Low-carbon manufacturing phase

The realisation of ACES vehicles will require an evolution of automotive manufacturing processes, changes in materials choice and vehicle function, which will consequently impact the facilities in automotive manufacturing plants, as follows [106]:

- The press shop which currently applies cold stamping will have to apply hot stamping and invest in die equipment required for the production of hot-stamped parts due to the increased use of advanced high-strength steel (AHSS), plastic, and carbon fibre composite parts [106]. Increasing the ductility of the hot-stamped parts is particularly of interest to the automotive sector, given their potential future use to produce complex shapes without cracking [97]. The hot stamping technology is expected to reach maturity by 2025 with effective speed and cost for mass production [97]. The future use of hot stamping technology will increase the importance of heat recovery in the stamping shop. The waste heat available in the cooling water of the hot stamping process can be used to drive heat pump or thermally-driven technologies [107]. In addition, injection and resin transfer moulding technologies are required for higher-volume production of plastic and carbon fibre composite parts, respectively [97,106]. The use of polymer composites for lightweight materials and part consolidation and the growing use of innovative manufacturing techniques, such as additive manufacturing and 3D stamping, are also expected in the future [106].
- The body shop will require significant modifications in the joining process in the future. Conventional techniques, such as resistance spot welding, would not be feasible any more due to the use of mixed materials and difference in their melting point [106]. Adhesive, fasteners, and laser welding are considered as the most promising approach for mixed-material joining but further research and development is required to manage the energy consumption of the process, particularly if compared to the current excellent cycle times and low-cost of resistance spot welding [106].
- The paint shop will also be affected by the change in the materials of the BIW, as follows:
  - o The high paint curing temperature will require particular attention with the forthcoming multi-material BIW, as materials expand differently about curing after curing, which could result in distortion of the body structure. After painting and curing, not rigid joints will be required to allow the multi-material vehicle to expand [106]. The temperature of the curing oven should be controlled for the future integration of sensors in CAVs [106].
  - o The E-coat process will be modified due to two main reasons: (i) E-coat is currently performed by treating the BIW material at the same time. The future multi-material mix of the vehicle will require a modification of the process of the chemical agents in the E-coat bath [35], (ii) the long-term corrosion resistance provided by E-coat will become less important for future shared vehicles, expected to last 3–4 years, due to their high mileage and reduced lifetime [106].
- The assembly shop will be mostly reshaped as additional components will be part of future vehicles, such as cameras, radar and lidar systems for CAVs, batteries for electric vehicles, and the related electronics [106]. All these additions will increase the complexity of the assembly process. The vehicle end-of-life inspection after assembly will become a critical and expensive process. Effective integration of the new components is hence one of the main challenges of the future automotive manufacturing industry and the use of artificial intelligence has been identified as a feasible strategy to overcome this problem.

The end-of-life treatment as well as remanufacturing, which uses 20–25% of the energy and 50% of the cost needed for the manufacturing of the same new product [103], will also be part of the automotive OEMs' strategies toward sustainability [108]. Following the ELV Directive and its increasingly stringent requirement to reutilise and recover their products by a minimum weight each year, automotive OEMs have started to implement remanufacturing strategies to a greater extent, resulting in reduced resource waste and improved environmental and economic benefits [103]. With the future development of electric vehicles, electrical and electronic waste is an issue, such as battery disposal and recycling, which will have to be taken into account. As such, remarkable opportunities for the optimisation of the future end-of-life management, recycling, and remanufacturing process are present.

For a more efficient utilisation of the available sources, a complete reformulation of the vehicle production in the design, manufacturing, and end-of-life phase based on circular economy strategy has been identified as a potential tool for enhancing the sustainability of the whole process, ensuring less market fragmentation and a better use of the resources [109]. In the future, vehicles will be designed for re-use and recovery of parts and/or materials, to reduce the dependency of the sector on raw materials and their fluctuating costs [110]. Through the implementation of a “closed-loop” business strategy established between different organisations including automotive OEMs and material and component suppliers based on (i) redesign of the supply chain and of the vehicle, (ii) reorganisation of material flows obtained by remanufacturing of components, (iii) reduction and utilisation of waste, and (iv) prolonged life of the vehicle [111], it is possible to obtain energy and material savings while obtaining remarkable benefits in terms of environmental burdens and energy consumption.

As previously seen for CAVs, higher integration of the software industry into the automotive sector is required for its sustainable development. Industry 4.0 is another software-based technology considered by automotive OEMs as a top priority towards the development of a low-carbon sector, significantly reducing the manufacturing energy consumption by increasing the supply chain efficiency and the manufacturing processes [112]. By the use of Radio Frequency Identification (RFID) technology and connected machining operation [113], the creation of a manufacturing process connected at digital level could result in remarkable benefits in terms of reduction of idle cycles and resulting energy-efficient use of the resources, increase of productivity, higher forecast accuracy, and reduction in plant maintenance cost [112].

To summarise, the conditioning and supply air to paint booths is responsible for high energy consumption, as described in Section 3.2. Substantial steps towards low-carbon manufacturing may be obtained with the use of technology to recover the low-temperature heat sources present (particularly compressed air and chilled water systems which are currently unexploited or less exploited in the paint shop) and efficiently control temperature and humidity as required by the paint booth. Potential innovative ASU units for paint booths and working decks need to use energy most efficiently for heating/cooling and de/humidification of the outdoor air. Liquid desiccant technology, based on the exploitation of the moisture absorption/desorption ability of hygroscopic solutions, such as mixtures of water with lithium chloride (LiCl), lithium bromide (LiBr), calcium chloride ($CaCl_2$) etc. could be particularly interesting for the application. The use of this thermally-driven technology in different fields of application, such as residential and commercial buildings and industrial sector, was previously described [90]. The idea of using this technology in the automotive painting process is novel. The opportunity of storing the excess heat present in the plant in the form of thermo-chemical energy in concentrated desiccant solution and transporting it without energy losses on-site is a research subject that deserves investigation by automotive OEMs in the future. As reviewed in Section 3.2 and Fig. 9, the vehicle painting process requires several steps of heating, cooling, dehumidification and humidification, consuming high energy for those. The multifunction ability of liquid desiccant technology for realising those processes makes the technology potentially appealing to automotive OEMs [114]. The technology could result in remarkable economic savings in terms of energy consumption (due to the efficient use of waste heat sources) and avoid paint defects and vehicle reworking after painting process, given the ability of the liquid desiccant technology in dealing with moisture and the importance of the latter for water-based paint. This is particularly true under cold climates, where the outdoor air ASU requires heating and humidification most of the year while the ARU with air recirculated from the paint booth requires cooling and dehumidification all the year round. Liquid desiccant technology may have the ability to simultaneously provide both processes. In addition, it is likely that vehicle manufacturing with powder-based painting process will be more common in the future. As such, the role of temperature and humidity control will be increasingly essential for the paint quality of the final product and the research on the most energy- and economy-efficient strategy will be a top priority to a greater extent for automotive OEMs.

5. Conclusions

To reduce the energy cost and environmental burden of manufacturing processes, automotive original equipment manufacturers focus on energy efficiency and thermal energy management practices. The article reviews the automotive manufacturing process and the steps undertaken by manufacturers towards the realisation of a sustainable sector, including: (i) the whole manufacturing process and related energy sources and uses, (ii) the paint shop, focusing on the description of the process in terms of energy sources employed and effect of the paint used on the painting process, (iii) energy efficiency practices and heat recovery strategies employed by automotive original equipment manufacturers in the whole manufacturing process and in the paint shop, and (iv) current and future steps of the automotive sector towards the realisation of a low-carbon sector in terms of evolution of vehicles (electric, connected and autonomous vehicles), of the materials used and of the manufacturing process.

This article demonstrates that vehicle production is a complex process, in which full knowledge is required for the evaluation of the next steps that can be achieved by the automotive industry with environmentally-friendly practices. It is believed that the review presented in this article can enhance the understanding of the whole process and of which steps are still needed, stimulating innovative ideas for energy efficiency, heat recovery and renewable energy practices.

The review showed that the paint shop is responsible for the highest energy consumption in the vehicle manufacturing process. This is due to the large amount of energy consumed (electricity, natural gas and chilled water) by air supply units which supplies air to paint booths. As a matter of fact, it is fundamental to effectively control temperature and humidity of the air in the paint booth to obtain a final product characterised by high quality and free of defects. This is particularly true for water- and powder-based paint developed in the last 30 years to limit the environmental impact of the painting process.

The findings suggested that a large potential for low-temperature heat recovery (at about 45–50 °C) is available from compressed air and chilled water systems in the paint shop and currently unexploited or exploited for applications not required all the year, such as space heating. In addition, the importance of temperature and humidity control for water- and powder-based paint makes the use of liquid desiccant technology in the paint shop very appealing due to its ability to be regenerated by low-temperature heat sources, being flexible (dehumidifier and regenerator can be located in separated positions) and effective in moisture control.

More information will be presented in another paper(s) focusing on the possible use of liquid desiccant technology in the automotive manufacturing plant, particularly in the paint shop. Optimally using low-grade heat from compressors and chillers and effectively controlling temperature and humidity in the paint booth would have the potential to reduce the consumption of electricity and natural gas and increase the quality of painting characterised by fewer defects, leading to significant economic and environmental benefits for the automotive original equipment manufacturers.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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